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ULTRASONIC DEFECT-SIZING USING DECIBEL DROP METHODS
VOLUME I: TEXT

by

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N.B. Research & Productivity Council

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Research report

ULTRASONIC DEFECT-SIZING USING DECIBEL DROP METHODS

ABSTRACT

Results are reported of a study performed to investigate the accuracy and repeatability of various ultrasonic decibel (dB) drop sizing methods in determining the length, vertical extent and orientation of artificial and real weld flaws in thin steel sections. Seven artificial flaws and nine real weld flaws were examined; over 200 data plots were produced.

The general findings are:

(a) length and vertical extent are assessed most accurately when using a 14 dB drop from the maximum indication amplitude;

(b) decibel drops less than 14 dB generally undersize flaws while decibel drops greater than 14 dB generally oversize flaws;

(c) flaws which are smaller than the width of the sound beam cannot be assessed accurately using dB drop mthods;

(d) large flaws are assessed most accurately when the sound beam strikes the flaws at near normal incidence;

(e) the vertical extent and orientation of large flaws are plotted most accurately using the beam centre line method as opposed to the beam profile method;

(f) the limitations of dB-drop-sizing methods have considerable ramifications for CAN3-N285.4-M83 and ASME XI evaluation criteria.

RÉSUMÉ

Le présent rapport fait état des résultats de l'étude qui a été effectuée pour juger à quel point les diverses méthodes d'évaluation ultrasonique de la taille des défauts par réduction du signal acoustique sont exactes et constantes d'une fois à l'autre, lorsqu'il s'agit de déterminer la longueur, l'étendue verticale et l'orientation des défauts artificiels et réels dans les soudures de sections d'acier minces. Sept défauts artificiels et neuf défauts réels de soudure ont été examinés; plus de 200 graphiques ont été produits.

Le rapport rend compte des résultats généraux suivants:

a) c'est en utilisant une réduction de 14 dB à partir de l'amplitude maximale que l'on peut évaluer le mieux la longueur et l'étendue verticale des défauts;

b) les réductions du signal acoustique inférieures à 14 dB sous-estiment ordinairement la taille des défauts, tandis que les réductions supérieures à 14 dB la surestiment généralement;

c) les défauts qui sont plus étroits que la largeur du faisceau sonore ne peuvent être évalués avec précision à partir des méthodes de chute de décibels;

d) c'est en s'assurant que le faisceau sonore frappe les défauts à l'angle d'incidence le plus rapproché de la normale qu'il est possible de déterminer le mieux la taille des défauts importants;

e) c'est en utilisant la méthode de la ligne centrale du faisceau plutôt que la méthode du profil du fraisceau qu'il est possible de déterminer le mieux l'étendue verticale et l'orientation des défauts importants;

f) les limitations des méthodes de mesure par chutes de décibels ont des ramifications très importantes pour la norme CAN3-N285.4-M83 et les critères d'évaluation de l'article XI du ASME Code.

"ULTRASONIC DEFECT-SIZING USING DECIBEL DROP METHODS"

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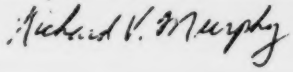

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PREFACE

The New Brunswick Research and Productivity Council (RPC) is pleased to have had the opportunity to perform this project. Many of the concerns, which led the Atomic Energy Control Board (AECB) to tender this project, have been experienced by RPC in its administration of past inaugural and inservice inspection programs.

RPC believes this project to be quite significant. RPC has contributed considerable non-chargeable time to this project and assigned it priority. RPC has strived to exceed all project objectives and deliver more than just quantitative size data. Attention has been drawn to phenomena which have been observed in the field. RPC has tried to provide a fundamental understanding of flaw/beam interaction, the practical difficulties and limits of search unit/work piece interaction and the influence of the ultrasonic operator on the inspection. This report provides answers to several pressing questions regarding the accuracy and repeatability of dB drop sizing methods. It also raises new questions that represent a challenge for future consideration.

FOREWORD

This report consists of two volumes:

Volume I contains the introduction, literature review, notes on ultrasonic measurements, observations, conclusions, recommendations, tables, figures and references.

Volume II - "Detailed Scans and Plots", consists of appendices A through E which present detailed ultrasonic scans and plots corresponding to the five test plates inspected.

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A. INTRODUCTION

1. Project Incentive

A variety of decibel drop techniques are currently in use for ultrasonic sizing of flaws in weldments during periodic inspection of Canadian nuclear power plants. Due the diversity of techniques and their application, the accuracy and repeatability of using the decibel drop approach in sizing flaws have become a matter of concern.

2. Project Objective

The project objective is to investigate the effectiveness of the decibel drop technique in sizing defects using beam axial and beam profile methods at several dB dropping levels.

3. Project Scope

(a) Assess the accuracy and limitations of the decibel drop technique for sizing defects in welds, piping, pipe fittings and pressure vessels.

(b) Compare the above with the requirements of CSA Standard N285.4-M83 (ASME V and XI), for the periodic inspection of nuclear power plant components.

4. Project Tasks

(a) Conduct a critical literature review to assess the effectiveness of the decibel drop technique for sizing defects;

(b) assess the accuracy and limitations of this technique using beam axial or beam profile at -1 dB, -6 dB, -12 dB, -14 dB and -20 dB levels;

(c) on the basis of the literature review, recommend, if appropriate, experimental work to confirm the accuracy and limitations of this technique;

(d) review and assess the requirements for, and the limitations of, equipment used with this technique;

(e) recommend the specific parameters required for a written procedure for each of the dB dropping levels, using beam axial or beam profile, listed in task(b); and

(f) prepare a report detailing the findings of Tasks (a) to (e) above.

5. Project Description

The flaws studied in this project were:
- Four rectangular EDM notches in the weld of a 20.4 mm steel plate.
- Two hemi-elliptical saw cuts in the weld of a 15.5 mm steel plate.
- One rectangular (square end) EDM notch in a 97.5 mm thick steel plate.
- Five real weld flaws including isolated slag, lack of penetration, blow holes and a slag line in the submerged arc weld of a 254 mm (10 inch) diameter, schedule 120, steel pipe (offcut of nuclear piping material).
- Four real weld flaws including burn through with associated slag, porosity and lack of penetration in the submerged arc weld of a 305 mm (12 inch) diameter, schedule 120, steel pipe (offcut of nuclear piping material).

The dB drop sizing methods investigated in this project were:
- 1 dB drop from maximum amplitude.
- 3 dB drop from maximum amplitude.
- 6 dB drop from maximum amplitude.
- 12 dB drop from maximum amplitude.
- 14 dB drop from maximum amplitude.
- 20 dB drop from maximum amplitude.
- drop from maximum amplitude to 100% of DAC (as per ASME Section XI).
- drop from maximum amplitude to 50% of DAC (as per ASME Section V and XI).

Thus, a variety of decibel drop techniques were used for ultrasonic sizing of artificial and real defects in the welds of steel components representing thin plate, thick pressure vessel plate and common pipe sizes requiring inservice inspection in Canadian nuclear power plants.

Definitions of the ultrasonic terms and abbreviations used in this report are provided in the section titled DEFINITIONS.

B. LITERATURE REVIEW

1. Methodology

The first task of the project was to conduct a critical literature review to assess the effectiveness of various dB drop methods for sizing defects. The survey began with a key-word search in two computer data bases, NTIS and METADEX. The resulting titles were reviewed and pertinent technical papers, books and reports were then acquired. A list of seventy one references is given in the BIBLIOGRAPHY. References in this report are denoted by [ ].

2. Research Trends

The literature indicated a tendency to shift research away from flaw sizing by conventional (manual) decibel drop sizing methods to more elaborate techniques such as synthetic aperture focusing (SAF) and time of flight analysis (TOF). This trend was particularly noticeable in the U.K.E.A. Defect Detection Trials [42], [49], [65], [66] and is reflected in the limited information on dB drop sizing revealed by this survey. Of the seventy one papers cited in the Bibliography, only sixteen have direct reference to the use of a typical dB drop method (6, 12 or 20 dB). Of these, eight compare two or more dB drop methods while the remaining eight are concerned with a single dB drop sizing method. The following two paragraphs provide comments on the relative accuracies of dB drop verses time of flight sizing techniques.

Farley and Dikstra of Babcock Power Ltd. [17], concluded that the performance of dB drop sizing methods (6 dB and 20 dB) is reasonable; "The successful results of straight forward techniques in the defect detection trials have more over shown that satisfactory performance need not rely on advanced techniques." More importantly, they make the point that; "accurate sizing needs precise measurement of echo range and probe position and needs a good understanding of the scattering of ultra sound from defects to allow proper interpretation of the observed responses".

Mudge and Jessop [40], reported good correlation between decibel drop and time of flight techniques, a conclusion based upon measured ultrasonic responses from some 50 weld defects of varying size in weld specimens of C:Mn steel of thickness ranging from 38 to 95 mm. They stated: "Typical errors (95% confidence limits) on planar defects cross-section measurement for a manual operator using the 20 dB drop probe movement method were +5.2, -7.2 mm of the true value". For time of flight techniques they stated: "While errors occurred in the time domain analysis technique ... it was the most accurate technique ... accuracies were +4.1, -3.1 mm". They also noted that higher accuracies were obtained sizing nonplanar defects; "errors in this case being +2.0, -3.6 mm and +1.7, -2.3 mm for the two techniques respectively".

3. Comparison of Different dB Drop Techniques

In reference to the 6 dB drop technique, Kupcis [34], stated: "The technique is reasonably accurate with increasing flaw size". This characteristic was also noted by Farley and Dikstra [17], who stated: "6 dB drop sizing of the resulting image gives a good approximation to the defect size (provided this is appreciably greater than the beam width)".

In reference to the 20 dB drop technique Kupcis [34] stated: "and is increasingly more accurate for defects smaller than the beam width. It is however, time consuming, requiring careful calibration, choice of equipment, and application under conditions which have been foreseen and explored".

In comparing the 6 dB and 20 dB drop sizing techniques, Jessop [32], stated: "with techniques such as the 20 dB drop, echo amplitudes are very small at the extremity points and may be lost in material and electrical noise if high testing sensitivities are required. (This limits usable testing sensitivity and can be a problem for investigation of weakly reflecting defects)". On the other hand, Schlengermann and Frielinghaus [54], noted: "On account of the variations in the echo amplitude of natural reflectors, the determination of the size and position is the more accurate the lower the threshold is set. Our results show that in most cases, the -6 dB threshold does not suit natural reflectors; 20 dB or more is required". McNab and Muir [39], seem to choose a middle road when they concluded that the sizing method applied (6 dB or 20 dB) should take into account the expected characteristics of a defect. "... This illustrates the errors which can arise when any single sizing method is used in two quite different reflecting situations".

4. Comments on ASME Section XI

Criticism of the ASME Section XI basic procedure was voiced by Whittle and Coffey [69]: "the plates used in the exercise (PISC) proved to contain many small inclusions and the consequent large number of signals breaking the 20% DAC recording level were difficult to cope with using manual scanning and without automatic data recording. Accordingly by agreement in the Plate Inspection Steering Committee, the recording level was raised to 50% DAC, thereby reducing the number of recordable echoes and speeding up the testing. This higher threshold of 50% DAC is that specified in the present Section XI of the ASME Code, but it nevertheless proved to be inadequate to ensure, with the probes used, reporting of several of the large defects in the blocks".

On operator repeatability, Jamison and McDearman [30] stated: "essentially the same results can be expected from one team inspecting the block several times and several teams inspecting the block one or more items each".

In regards to ultrasonic equipment, Jamison and McDearman [30] stated: "on average, relatively broad band width instruments will size indications larger and at higher amplitudes compared to relatively narrow band width instruments. This indicates that two examinations, both meeting the requirements of ASME Section XI, can produce significantly different results when instruments with different characteristics are used". The comments of Jamison and McDearman imply that unless the characteristics of a testing system (probe and flaw detector) are known, significant errors in the final reported results could occur. This concern was also expressed by Cook [12]: "Finally, it is recommended that the beam spread curves for each search unit/instrumentation setup be used as a standard of reference and cross checked for repeatability prior to each subsequent inspection". Watkins and Cowburn [65] stated: "Although many inspection agencies carry out their own checks on probes and equipment, there is a need for a tighter specification of the important variables, e.g., frequency, beam profile, display and data collecting equipment used for ISI applications".

5. Literature Review Conclusions

The following conclusions were drawn from the literature review.

(i) Few published articles exists which directly compare the performance of two or more dB drop sizing methods. In general, definitive, reproducible, quantitative data, relevant to the accuracy of the various dB drop sizing methods, is not presented.

(ii) Most of the literature concerning dB drop sizing used artificial defects as opposed to actual weld/material defects. There appears to be scant data comparing of the effectiveness of dB drop sizing methods using both real and artificial defects.

(iii) No reference was found to a comparative investigation of sizing methods based upon dB drop (6, 12, 20 dB) from maximum amplitude and the ASME Section V and XI drop to a fixed percentage of DAC. In addition, no reference was found to the requirements of CSA Standard N285.4.

(iv) Errors in flaw sizing with dB drop methods, caused by variations in the flaw geometry, surface coupling and weld geometry, have not extensively been investigated.

(v) Traceable and documented calibration is vital for reproducible results.

In view of the above findings of the literature survey, the objectives and tasks of this project appear to be well chosen to address these concerns.

C. BACKGROUND TO ULTRASONIC MEASUREMENTS

1. CSA Standard and ASME Code Requirements

A review was made of the requirements of Canadian Standard Association (CSA) Standard CAN3-N285.4-M83 and American Society of Mechanical Engineers (ASME) Code Section V (1983) and Section XI (1983). The Atomic Energy Control Board (AECB) directed the New Brunswick Research and Productivity Council (RPC) to confine standard and code related comments to the 1983 revisions. There are nuclear plants built and operating under previous and quite different issues of these standards and codes. The evaluation and disposition of indications in the weld zone is different in CSA Preliminary Standard N285.4-1975 and CSA Standard N285.4-M1978 and both are significantly different from standard CAN3-N285.4-M83, which introduces evaluation per ASME code Section XI. ASME Section V has changed over the past years. Comments on these previous standards and codes is outside the bounds of this project.

1.1 Standard and Code Sizing Thresholds

The review of CAN3-N285.4-M83, and ASME Sections V and XI (1983) revealed that a variety of threshold levels are currently in use for determining flaw size. These comprise drop from peak amplitude to:

- 50% of the Distance Amplitude Correction curve (DAC).
- 100% of the reference level (same as 100% DAC).
- 50% of peak amplitude (same as 50% of maximum amplitude or 6 dB drop from maximum amplitude).

Thus, there are two different classifications of threshold based upon:

(i) decreasing a maximized indication's amplitude by a chosen ratio, a fixed number of decibels (an example of this is the 6 dB drop technique which drops a maximized indication's amplitude by 6 dB, i.e., to 1/2 or 50% of its original value. Thus, 6 dB drop from maximum amplitude and drop to 50% of maximum amplitude are two ways of saying the same thing); and

(ii) decreasing a maximized indication's amplitude to a chosen level, usually some percentage of DAC (an example of this technique is the 50% DAC drop technique which drops a maximized indication's amplitude to 50% of DAC. Similarly, a 100% DAC drop technique drops a maximized indication's amplitude to 100% of DAC).

It is important to recognize that classifications (i) and (ii) above are quite different. Dropping a maximized indication's amplitude to 50% of maximum amplitude is not the same as dropping it to 50% DAC. Sizing by these quite different techniques could well yield different results.

RPC felt that the project should determine the comparative accuracy of each classification. The project tasks required investigation of only decibel drop techniques; -1 dB, -6 dB, -12 dB, -14 dB and -20 dB. RPC added -3 dB drop and the ASME percentage DAC drop techniques; 50% DAC and 100% DAC.

CSA Standard CAN3-N285.4-M83 requires, for periodic inspection of indications whose amplitude exceeds 100% DAC, that reflector orientation be determined as either normal (+ or - 60 degrees) or parallel (+ or - 30 degrees) to the surface. RPC endeavoured to assess the ability of the various sizing techniques to determine reflector orientation.

According to CSA Standard CAN3-N.285.4-M83, for reflectors parallel to the surface the maximum acceptable length 'A' is A=6 mm for wall thickness 'T' less than 20 mm, A=T/3 for thickness 20 mm to 60 mm and A=20 mm for thickness above 60 mm. RPC strived to determine if the various sizing methods are capable of meeting these criteria.

The limitations of the various sizing methods found during this project and their ramifications with respect to CSA Standard CAN3-N.285.4-M83 and ASME Sections V and XI is discussed in Section F of this report.

2. Test Specimens

Key to the nature of the project was the acquisition of test specimens containing real and artificial weld defects, sampling the Canadian nuclear piping, pipe fittings and pressure vessels. In an attempt to obtain suitable test specimens, RPC contacted several Canadian companies including Babcock & Wilcox, DOFASCO, INCO, ALGOMA STEEL, Energy Mines and Resources (EMR) and Atomic Energy of Canada Limited - Chalk River Nuclear Laboratories (CRNL). DOFASCO and INCO had cracked forgings and castings, but their size and weight prohibited shipment to RPC. EMR had seven steel test plates about 25 mm thick containing artificial weld defects. Unfortunately, these plates had backing strips on the weld underside, making them unsuitable as examples of nuclear component welds. ALGOMA STEEL was able to supply 50 and 100 mm thick steel plate of pressure vessel thickness, but the material arrived too late to be used in the project. CRNL shipped to RPC, three (250 mm x 100 mm x 10 mm thick) and one (250 mm x 100 mm x 20 mm thick) specimens of pipeline steel containing real defects. However, the defects were in proximity to the weld root, so clear defect echoes needed for evaluation of the sizing techniques could not be obtained. As a result, the CRNL specimens were not used.

Having been unsuccessful in obtaining suitable test specimens from other firms, RPC used in-house pipe weld specimens and fabricated additional plate weld specimens representative of the thickness range encountered in Canadian nuclear component inspection.

2.1 Test Plate #1

The first specimen, test plate #1, was designed to assess the inherent accuracy of the various decibel drop sizing techniques. Test plate #1 features EDM slots as artificial flaws. The EDM slots maintain their dimensions constant until ending abruptly with ninety degree corners. Ultrasonically, this shape should feature uniform reflecting surface, constant reflecting area and most importantly, sharply defined ends. Thus, the lengths of the flaws are accurately known and may easily be compared to the results obtained by ultrasonic sizing methods. Flaw lengths of about 52 mm were chosen to be larger than the width of the ultrasonic beams so that the length of the flaw, not the width of the sound beam, would be measured.

Test plate #1 was fabricated from 20.4 mm thick mild steel (CSA 350WT). The welded plate (single V, 60 degree included angle, back-gouged, submerged arc) was supplied to RPC by Saint John Ship Building Limited. Directly into the weld of this plate, five artificial flaws, EDM slots approximately 0.35 mm wide and 52 mm in length, were burned through the plate thickness. A 10 mm wide area around each EDM slot, was machined with an end mill and then welded over (stick process) to seal the slots within the body of the weld. Weld crown and weld root bead were ground flush with a hand grinder. The plate was then radiographed to verify that the welding had not altered the original dimensions and positions of the slots within the plate. While no apparent change in slot dimensions occurred, the radiographs showed lack of fusion about both ends of the end mill cut of Flaw #3. The position, dimensions and orientation of the flaws are described below and are shown in Figure 1.

Test plate #1: thickness = 20.4 mm, (NOTE: A = A Coordinate in mm).
Artificial flaws: EDM slots featuring square ends, 0.35 mm (0.016 inch) wide.
Flaw 1: A = 40 to 98, length 58.0 mm, located at top surface, vertical orientation, 5.0 mm through-wall dimension.
Flaw 2: (not used) A = 185.5 to 238, length 52.5 mm, top, vertical, 5.0 mm.
Flaw 3: A = 321 to 373, length 52.0 mm, located in middle of plate, vertical orientation, 5.0 mm through-wall dimension.
Flaw 4: A = 462 to 515, length 53.0 mm, located at top surface, orientation 30 degrees to vertical, 5.0 mm through-wall dimension.
Flaw 5: A = 605 to 656.5, length 51.5 mm, located in middle of plate, orientation 30 degrees to vertical, 5.0 mm through-wall dimension.

Basic block: NAV1, 19.5 mm thick, 2.38 mm (3/32 inch) diameter side drilled holes at 1/4 T and 1/2 T (T = thickness of basic block).

2.2 Test Plate #5

The second specimen, test plate #5, features rotary saw cuts as artificial flaws. The flaws continuously break the surface, are canoe like in shape having curved ends and their linear surface and shorter subsurface lengths are accurately known. The "actual length" of these flaws was taken to be the longer surface length. These flaws simulate the run out of a crack to the surface. The ultrasonic sizes of these artificial flaws may provide a closer approximation to the sizing results likely to be achieved on real weld defects, which do not exhibit the ninety degree corners of EDM slots in test plate #1. Flaw lengths of about 37 mm were chosen to be larger than the width of the ultrasonic beams so that the length of the flaw, not the width of the sound beam, would be measured.

Test plate #5 was fabricated from 15.5 mm thick mild steel (CSA 350WT). The welded plate (single V, 60 degree included angle, back-gouged, submerged arc) was supplied to RPC by Saint John Ship Building Limited. Directly into the weld of this plate, two artificial flaws of surface length about 37 mm and through-wall dimension of about 6 mm were made using a 69.85 mm (2.75 inch) diameter, 0.406 mm (0.016 inch) thick, rotary slitting saw. On the top surface of the plate, weld crowns were not ground. On the bottom of the plate, only the root weld bead about flaw #2 was ground flush, flaw #1 remaining in the root weld bead. The position, dimensions and orientation of the flaws are described below and are shown in Figure 2.

Test plate #5: thickness = 15.5 mm, (NOTE: A = A Coordinate in mm).
Artificial flaws: 69.85 mm diameter, 0.406 mm rotary slitting saw cuts.
Flaw 1: A = 70 to 109, length 39.0 mm, vertical orientation, located in root weld bead, 6 mm below top of weld crown.
Flaw 2: A = 213 to 249, length 36.0 mm, vertical orientation, located in ground flush root weld bead, 5.6 mm below top of weld crown.

Basic block: NAV2, 15.5 mm thick, 2.38 mm (3/32 inch) hole at 1/2 T.

2.3 Test Plate #6

The third specimen, test plate #6, was designed to assess the accuracy of the various decibel drop sizing techniques for determining flaw vertical extent and orientation. Test plates #1 and #2 featured artificial flaws of long length but short vertical extent in thin plate. Test plate #6 simulates thick pressure vessel material having a defect of significant vertical extent. Test plate #6 contains a single EDM slot (0.35 mm wide, 15 mm in length) of large vertical extent (60 mm) in a 97.5 mm thick steel block. The EDM slot ends abruptly with ninety degree corners providing a target of known orientation and vertical extent for assessing the various dB drop sizing techniques.

Test Plate #6 was fabricated from 97.5 mm thick, 75 mm wide, 440 mm long section of mild steel bar stock. The top and bottom surfaces of the block were milled such that the vertical extent of the flaw would be 60 mm (51 mm through-wall dimension). A 0.35 mm wide EDM of length 15 mm was burned through the milled plate at an angle of 30 degrees to the surface normal as shown in Figure 3A. This angle was chosen at a usual weld preparation angle and the flaw could be considered to simulate a large lack of side wall fusion. The milled areas were then welded over (stick process) and the top and bottom surfaces ground flush. The position, dimensions and orientation of the flaw are described below and are shown in Figure 3B.

Test plate #6: thickness = 97.5 mm, (NOTE: A = A Coordinate in mm).
Flaw: EDM slot 0.35 mm wide, 15 mm length, 60 mm vertical extent, 51 mm through-wall thickness, oriented 60 degrees to surface.

Basic block: Test plate #6, 4.763 mm (3/16 inch) side drilled hole at 1/4 T.

2.4 Test Plate #10

The fourth and fifth specimens are pipe to pipe welds containing real weld defects purposely introduced during the welding process. Weld preparations are single V, J type and the welding process is submerged arc. The specimens, fabricated from offcuts of Point Lepreau NGS piping material (ASTM - A106B), were purchased along with documenting radiographs by RPC in 1979 from Universal Pipeline Enterprises Limited, Montreal.

The fourth specimen, test plate #10, is a section of 254 mm (10 inch) diameter, schedule 120 (22.5 mm thick) nuclear grade pipe featuring widely separated real weld defects; slag, porosity, lack of penetration and blow holes in a circumferential submerged arc weld. The radiographic position and dimensions of the flaws are described below and are shown in Figure 4.

Test plate #10: 254 mm diameter, schedule 120 (22.5 mm thick) pipe.
Flaw 1: slag, A = 115 to 128, length 13 mm, depth = 9 mm.
Flaw 2: porosity, A = 307 to 360, length 53 mm, depth = 13.5 mm.
Flaw 3: slag line, A = 472 to 580, length 108 mm, depth = 17-19 mm.
Flaw 4: lack of root penetration, A = 707 to 716, length 9 mm, depth = 22 mm.
Flaw 5: blow holes, A = 750 to 801, length 51 mm, depth = 22 mm.
(NOTE: A = A Coordinate in mm).

Basic block: NUC1, 254 mm (10 inch) diameter, schedule 80 (19.5 mm thick) nuclear pipe offcut with 2.38 mm (3/32 inch) side drilled holes at 1/4, 1/2 T and 3/4T.

2.5 Test Plate #12

The fifth specimen, test plate #12, is a section of 305 mm (12 inch) diameter, schedule 120 (25 mm thick) nuclear grade pipe featuring widely separated real weld defects; slag, porosity, burn through with associated slag and lack of penetration in a circumferential submerged arc weld. The radiographic position and dimensions of the flaws are described below and are shown in Figure 5.

Test plate #12: 305 mm diameter, schedule 120, (25.0 mm thick) pipe.
Flaw 1: burn through/slag, A = 197 to 227, length 30 mm, depth = 15 mm.
Flaw 2: porosity, A = 638 to 646, length 8 mm, depth = 13 mm.
Flaw 3: burn through/slag, A = 828 to 880, length 62 mm, depth = 20 mm.
Flaw 4: lack of penetration, A = 930 to 950, length 20 mm, depth = 20 mm.
(NOTE: A = A Coordinate in mm).

Basic block: NUC1, 254 mm (10 inch) diameter, schedule 80 (19.5 mm thick) nuclear pipe offcut with 2.38 mm (3/32 inch) side drilled holes at 1/4, 1/2 T and 3/4T.

3. Calibration Blocks

The following ultrasonic calibration blocks were used during the project:

IIW Block: S/N=1 was used to measure search unit exit point, angle and to perform functional power checks.

DIN 54-122 block: S/N=786246 was used to calibrate instrument screen (CRT) ranges.

IOW block: S/N=1 was used to measure sound beam widths in order to make beam profiles diagrams.

Basic block NAV1: 19.5 mm thick of the same steel as Test Plate #1, contains two holes (1/4 T and 1/2T) of 2.381 mm (3/32 inch) diameter and was used to produce DAC curves for Test Plate #1.

Basic block NAV2: 15.5 mm thick of the same steel as Test Plate #5, contains one hole (1/2T) of 2.381 mm (3/32 inch) diameter, and was used to produce DAC curves for Test Plate #5.

Basic block NUC1: an offcut of schedule 80, 254 mm (10 inch) pipe, contains three holes (1/4T, 1/2T and 3/4T) of 2.381 mm (3/32 inch) diameter, was used to produce DAC curves for use with 254 and 305 mm diameter, schedule 120, pipe specimens Plate #10 and Plate #12.

Test plate #6: 97mm thick mild steel pressure vessel simulator, contains a 3/16 inch (4.763 mm) diameter hole at the 1/4T position. This hole was shot at various vee paths to make DAC curves for test plate #6 as per ASME Section V.

Basic Block RPC1: 100 mm thick, 50 mm wide and 250 mm long, mild steel containing 1.5 mm diameter side drilled holes at depths of 1, 5, 7, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55 and 60 mm. This block was used to extend DAC curves of other basic blocks and to assist in establishing electronic DAC.

4. Ultrasonic Equipment

The ultrasonic instruments, search units and couplant used during this project were chosen to be representative of the equipment in current use for inservice inspection of Canadian nuclear power plants.

(i) Instrument: Krautkrammer USL-38, S/N = 210780

(ii) Search unit: Aerotech MSWS Gamma (medium damped) transducer, S/N=40084, style 3 (threaded case), 12.7 mm diameter disk shaped crystal with 2.25 MHz centre frequency. This unit was used to perform all ultrasonic measurements during this project.

Three Aerotech MSWS angle beam wedges (threaded with black material at front of wedge) of measured angles 45, 60 and 70 degrees were used with the above transducer.

(iii) Couplant: Couplant used between the transducer and the wedges was SAE 10W30 motor oil.

Couplant used between the wedge and work piece for all calibration and scanning was identical to that in current use for CANDU inservice inspections, 'Hamikleer', a product of the Harvey Miller Corporation.

5. Calibration

The calibration, verification and documentation requirements of ASME Section V were exceeded. RPC made a strong effort to ensure that measurements were accurate and documented in such a way as to be reproducible in the future.

Instrument vertical, amplitude control and time base linearity were measured, documented and verified to be within + or - 3% before and after each major test sequence and at weekly intervals during scanning. The instrument remained within acceptable limits throughout the project.

Six, twelve and twenty dB search unit beam profiles for the 45, 60 and 70 degree units were prepared using an IOW block at the beginning and verified end of the project. The averaged, smoothed results of these beam profiles are illustrated in Figures 6, 7 and 8 respectively. The small size of the IOW side drilled holes gave quite low echo amplitudes making accurate measurement of the 20 dB beam profile difficult especially with the 70 degree angle.

The centre operating frequency of the search units were measured and documented at the beginning and end of the project and found to remain constant at 2.2 MHz + or - 10%.

Search unit index point (limit + or - 1 mm), beam angle (limit + or - 2 degrees) and power verification (limit + or - 12 dB) were measured and documented before and after each specimen inspection and every day prior to inspection. Search unit index points measured angles (45, 60 and 70) remained constant, exactly as marked on the units. Function power checks remained within + or - 2 dB of the original value through the project.

Daily basic block DAC calibrations were cross referenced to the functional power check, the response from the 1.5 mm side drilled hole in the IIW block. DAC calibrations remained constant within + or - 1 dB through the project.

Ancillary recording equipment was calibrated or verified daily or for each scan of a flaw. This calibration was for such items as instrument peak detector linearity, xy-chart recorder vertical linearity, digital counter trigger threshold and its dc analog output to xy-chart recorder.

Distance Amplitude Correction (DAC) curves, were prepared on the appropriate basic calibration block used with each of the test specimens. The DAC curves used are illustrated in the appropriate appendices of this report. Electronic DAC, used in recording vertical extent signatures, was held within + or - 1 dB over the entire maximum CRT range for each search unit used.

6. Flaw Scanning

Ultrasonic scanning of all flaws was performed in accordance with the general provisions of ASME Section V. The primary reference response for all flaws was an 80% full screen height (FSH) echo amplitude from the primary reference target; a 3/4T side drilled hole at 3/8th of a full vee sound path.

Whenever the DAC curve rose above 80% FSH or dropped below 20% FSH, additional 10 dB lower or higher gain DAC curves were added to the instrument screen. This allows flaws to be properly evaluated throughout the range from 1/8th to 11/8th of a full vee sound path. This ensured that indications occurring within this screen range could be properly recorded. Because of the research nature of this project, DAC curves were often extended (in order to evaluate near surface or distant flaws) by using basic block RPC1. This block was also used to assist in establishing electronic DAC. Distance amplitude correction data for basic block RPC1 is provided in Table 1.

All ultrasonic scanning was performed by hand in the manner consistent with current practice in Canadian nuclear power plants. Mr. John A. Capar (RPC) was the principal ultrasonic operator. Mr. Capar is a certified Canadian Government Standards Board (CGSB) Level II ultrasonic technician with 8 years of practical scanning experience in the inaugural and all past inservice inspections of Point Lepreau NGS and the inaugural inspection of Wolsung 1 NPP. Additional scans were performed by Dr. Richard V. Murphy (RPC), a CGSB certified Level III ultrasonic technician with 9 years of practical scanning experience in the inaugural inspection of Point Lepreau and past inservice inspections of both Point Lepreau NGS and Wolsung 1 NPP.

For each angle, the weld was scanned from both sides of the weld and from both the top and bottom of the plate. In addition, indication response has been documented where possible at half, full and one and a half skip positions. Thus, as many as 12 separate scans of length and 12 separate scans of vertical extent may be available for each search unit angle examination of a "flaw".

7. Manual Recording of Data

At the start of the project, all data were recorded manually as per inservice inspections at Canadian nuclear power plants. This process consists of the following steps:

(i) At the search unit location corresponding to maximum echo amplitude from a flaw, the operator marks (with a coloured pencil) on the work piece, the position of the search unit index point and search unit centre line. The operator calls out the CRT distance to his helper.

(ii) The search unit is moved laterally to determine the length of the flaw and the end point positions and CRT distances are recorded as in (i).

(iii) The search unit is moved forwards and backwards to find the vertical extent of the flaw and the end points and CRT distances are recorded as in (i).

(iv) The search unit is removed from the work piece and the five positions marked on the work piece are called out by the operator to the helper who records them on a paper form designed for this purpose.

For this project, the use of a two-man team was not possible due to economic restraints and the ultrasonic operator wrote the pertinent information on rough work sheets. After completing a scan as in (i) through (iv) above, he would wash his hands of couplant and then transfer the data to paper forms. This process was found to be very time consuming in view of the large number of indications and dB drop levels being evaluated. A single reflector could be examined from four possible sides (top left, top right, bottom left and bottom right), each side providing up to three possible indications (prior half skip, prior full skip and prior skip and a half). For each of these indications, separate scans were required for -1, -3, -6, -12, -14 and -20 dB drops from maximum amplitude as well as drop to 50% DAC and 100% DAC. This had to be done for three different angles; 45, 60 and 70 degrees. Thus, the evaluation of a single flaw could result in a total of 4x3x8x3 = 288 scans. Recording four flaws in the first test plate with a 70 degree search unit required 10 days.

The manually recorded data was reviewed by RPC and AECB. While it provided useful initial results, it was found to be lacking the necessary detail to reveal why certain phenomena were occurring. As a result, all later 70 degree scans and also all of the 60 degree and 45 degree scans were performed by hand movement of the search unit but with a mechanical/electronic data logging.

The mechanical/electronic data logging method captures the entire indication envelope ("signature") as the search unit scans the reflector. This has the benefit of providing much more detailed information such as length and vertical extent signatures (continuous traces of amplitude verses probe position and CRT distance). Previously, manual scanning limited choice of dB drop to a few discreet selections such as -1, -3, -6, -12, -14 ,-20. The signatures permit any dB drop from 0 to -20 to be observed. More importantly, the signatures clearly show the effects of coupling variations, surface undulations, multiple peaks, and explain how and why under or over estimates of length and vertical extent occur.

8. Mechanical/Electronic Data Recording

The system used for data recording is shown in Figure 9. The work piece is manually scanned to locate the reflector. The search unit is manipulated to obtain the maximum amplitude of the indication and the A, B coordinates, CRT distance and amplitude of the indication are recorded in the normal manner.

8.1 Recording Length

Without moving the search unit, a straight edge guide is placed flush against the front or back of the search unit and fixed to the work piece by means of strong magnets as shown in Figure 10. The guide ensures linear tracking of the search unit, side to side, for length measurements. A rigid metal rod is used to link the search unit to the x-axis of an xy-chart recorder. The recorder pen is lowered and the pen moved manually up and down to establish an A coordinate datum on the sheet of graph paper held in the xy-chart recorder. The pen is raised and the actual A coordinate is written on the graph paper as well as the B coordinate, CRT and maximum amplitude of the indication.

The following process is used to document the length of a reflector. The ultrasonic instrument time gate is turned on and positioned to just encompass the width of the maximized indication. The search unit is moved along the guide until the screen indication decreases to zero amplitude. The recorder y-axis servo motor is turned on so that the pen may track and plot the peak amplitude of the indication. The search unit is then slowly moved by hand back along the guide until the indication rises through maximum amplitude and then decreases to finally disappear from the instrument screen. As this lateral length scan is in progress, the xy-chart recorder plots a continuous track of the peak echo amplitude (y-axis) verses search unit A coordinate (x-axis). The resultant indication envelope is a permanent record of the entire length scan of the reflector and is referred to as a "length signature".

8.2 Recording Vertical Extent

When measuring reflector length, the search unit is moved laterally, usually maintaining constant the CRT distance to the reflector. The indication's amplitude changes only due to sound beam interaction at the target. When measuring reflector vertical extent however, the search unit is moved towards or away from the reflector. The indication's amplitude changes not only due to sound beam interaction at the reflector but also due to distance amplitude attenuation caused by changes in the CRT distance. The operator compensates for the later effect by using a DAC curve drawn on the instrument screen. To obtain distortion free plots of amplitude verses B coordinate on an xy-chart recorder it is necessary to use electronic DAC to compensate for this effect.

The following process is used to document the vertical extent of a reflector. The search unit is repositioned to maximize the amplitude of the indication. Without moving the search unit, the straight edge guide is placed flush against one side of the unit and fixed to the work piece by means of magnets as shown in Figure 11. The guide ensures linear tracking of the search unit forwards and backwards during vertical extent measurements. The xy-chart recorder is positioned and the rigid metal rod from the x-axis is fixed to the search unit. The recorder pen is lowered and the pen moved manually up and down to establish a B coordinate datum on the sheet of graph paper held in the recorder. The pen is raised and the actual B coordinate is written on the graph paper together with the A coordinate, CRT distance and maximum amplitude of the indication. The instrument time gate is turned on and positioned to just encompass the width of the indication. The search unit is moved backwards along the guide until the indication decreases to zero amplitude.

Two separate scans over the reflector are required to provide a continuous record of indication amplitude, search unit B coordinate and CRT distance from the search unit to the indication. The first scan plots peak amplitude verses B coordinate, the second scan will overlap the first and plots CRT distance verses B coordinate.

For the amplitude verses B coordinate scan, the search unit is slowly moved by hand forward along the guide until the indication rises through maximum amplitude and then decreases to zero amplitude. As this vertical extent scan is in progress, the xy-chart recorder plots a continuous track of the peak echo amplitude (y-axis) verses search unit B coordinate (x-axis).

For the CRT distance verses B coordinate scan, the search unit is returned to the start positioned for the amplitude verses B coordinate scan. The xy-chart recorder y-axis servo is connected to the output of a digital counter. The digital counter displays the elapsed time from the initial pulse to the first echo in the instrument time gate which rises above a certain percentage (5%) of full screen height. The y-axis servo motor is turned on so that the pen may track and plot the CRT distance to the indication. The search unit is then slowly moved by hand forward along the guide until the indication rises through maximum amplitude and then decreases to finally disappear from the instrument screen. As this vertical extent scan is in progress, the xy-chart recorder plots a continuous track of CRT distance (y-axis) verses search unit B coordinate (x-axis).

The resultant overlapping plots (peak echo amplitude verses B coordinate and CRT distance verses B coordinate) form an indication envelope that is a permanent record of the entire vertical extent scan of the reflector and is referred to as a "vertical extent signature".

9. Data Presentation

The length and vertical extent signatures contain a great deal of information. Extracting numerical size data from these analog graphic plots can be done manually but it is very time consuming for two reasons:

(i) The output of the peak detector of the USL-38 instrument used is increasingly nonlinear below about 15% FSH or above 90% FSH. Thus, 8% on the analog graphic plot may actually represent an echo height of 5%. Correction must be made for the instrument peak detector nonlinearity before attempting to extract size information.

(ii) The analog signatures are not all of the same height. This is so because of variations in coupling of approximately + or - 2 dB which occurred during physical movement of the search unit over the work piece surface. This does not affect the accuracy of the size information. Yet, it does require the use of either a changing scale or the prior normalization of the indication height to extract size information.

With final report presentation in mind, it was recognized that it would be necessary to reproduce several of these signatures, adding labelled axes, indicate the plate, flaw, type of shot and additional pertinent information. Manual drawing would be too time consuming and the use of a microcomputer drawing package seemed appropriate. It was therefore decided to convert the analog signature plots into computer digital data by tracing over the analog plots on a high resolution digitizing tablet as shown in Figure 12. The computer was programmed to remove the peak detector nonlinearity and to normalize the plots to the same height. The computer calculated the dB drop sizes for -1, -3, -6, -12, -14, -20 dB, 100% DAC, 50% DAC and produced fully labelled signatures suitable for inclusion in the final report. Size resolution is + or - 1 mm.

NOTE: **The computer signatures are as accurate as the original analog data and enable other researchers to extract accurate information from these plots which would otherwise be impossible.**

This project generated a substantial amount of data. First thoughts were to attempt to choose typical results for a compact presentation. This idea was rejected since the selection process could introduce a bias into the presented results. Therefore, it was decided to present all the data in five appendices corresponding to the five test plates examined. Thus, data for test plate #1 is presented in Appendix A, test plate #5 in Appendix B, test plate #6 in Appendix C, test plate #10 in Appendix D and test plate #12 in Appendix E. These appendices are contained in Volume II - Detailed Scans and Plots.

D. OBSERVATIONS

1. Artificial and Real Weld Flaws

This section presents a number of observations which were noted during ultrasonic scanning and review of the data in appendices A through E from:

Test plate # 1: 20.4 mm thick, with four rectangular EDM slots in the weld.
Test plate # 5: 15.5 mm thick, with two hemi-elliptical saw cuts in the weld.
Test plate # 6: 97.5 mm thick, with one rectangular (square end) EDM slot.
Test plate #10: 254 mm (10 inch) diameter, schedule 120 (22.5 mm thick) with pipe, slag, porosity, slag line, lack of penetration and blow holes in the weld.
Test plate #12: 305 mm (12 inch) diameter, schedule 120 (25.0 mm thick) pipe with slag, porosity, burn through and lack of penetration in the weld.

2. Observations on Maximum Amplitude of Indications

Difficulty in repeating previous readings of the maximum amplitude of indications occurred when the surface of the test piece exhibited surface contour variations. Minor surface changes cause coupling variations due to uneven search unit glide (sticking) and search unit pitch or roll sufficient to affect the amplitude of the echo. In such cases, there may be a particular location on the work piece ("sweet spot") at which the echo amplitude is higher (up to 3 dB) than in immediately adjacent positions.

Certain reflectors exhibit two or more peaks of similar amplitude in their echo envelopes. Small changes in search unit position and orientation may the cause a reversal in the apparent amplitude order of the peaks. If a different peak is recorded as the maximum, this can cause an apparent change in the recorded amplitude, surface location and depth of the reflector.

In general, the maximum echo amplitude of a reflector was found to be very repeatable, usually within + or - 1 dB and seldom outside of + or - 2 dB. This was so with different inspectors and with scans repeated weeks apart.

The excellent repeatability of maximum amplitude is attributed to the great freedom allowed the ultrasonic inspector to manipulate the ultrasonic search unit (forwards, backwards, side to side, roll and yaw) while closely observing the dynamics of the echo on the flaw detector screen. The inspector can vary the hand pressure applied to the search unit, remove it from the work piece (to avoid surface sticking), add more couplant and try again.

3. Observations on Length Measurement Techniques

3.1 Test Plate #1

The ultrasonic lengths, as determined by lateral search unit movement, of four rectangular EDM slots in test plate #1, were found to be most accurate when the sound beam angle was such to strike the flaw at near normal incidence and the 12 dB drop sizing method was used. However, when all three inspection angles were used (45, 60 and 70 degrees), the ultrasonic measured lengths were found to be most accurate and repeatable when employing a decibel drop from maximum echo amplitude of 14 dB. Accuracy statistics for the EDM slots in test plate #1 are presented in Table 2.

Certain flaws were able to be sized at a variety of CRT distances. Sizes obtained at medium CRT distances (2/8th to 8/8th vee path) tended to be most accurate. Sizes obtained at very short CRT distances (below 2/8 vee path) tended to be somewhat short. This is caused by multiple echo peaks generated by examining a flaw in the near field of a search unit. At short distances, small changes in search unit orientation cause large changes in indication amplitude. Sizes obtained beyond 9/8th vee path tended to be somewhat long. This is caused by the sound beam expanding to a width greater than the flaw.

3.2 Test Plate #5

The ultrasonic lengths of two hemi-elliptical saw cuts in test plate #5 were found be most accurate and repeatable when employing a decibel drop from maximum amplitude of 17 dB to 20 dB. Accuracy statistics for the saw cuts in test plate #5 are presented in Table 3.

3.3 Test Plates #10 and #12

The ultrasonic lengths of real weld flaws in test plates #10 and #12 were found to be most accurate and repeatable when employing a decibel drop from maximum amplitude of 14 to 20 dB. Only six of the eleven weld flaws had actual lengths sufficiently long (greater than the width of the sound beam) to permit ultrasonic length measurement and these results are presented in Table 4. Of these six flaws, three (P10L5, P12L1 and P12L4) sized reasonably well by 14 dB drop and two (P10L2 and P12L4) sized well by 20 dB drop. Two flaws, (P10L3 and P12L3) were considerably undersized by both the 14 dB and 20 dB drop methods and seem to require a dB drop considerably greater than 20 dB to produce an accurate ultrasonic length estimate. Decibel drops below 14 dB (-1,-3, -6 and -12 dB) consistently under estimated flaw lengths. The 14 dB drop level appears to represent the end of this trend. At the 20 dB drop level, flaws may be undersized, correctly sized or oversized. Unfortunately, the 20 dB drop method exhibited a frequent tendency to grossly oversize flaw length which was most disturbing.

3.4 General Length Observations - All Flaws

(i) Very small dB drops from maximum echo amplitude, such as -1 dB, were found to be impractical. The variation in surface coupling and the repeatability of the maximum echo response exceeds this value. Using such a technique, reflectors were always grossly undersized.

(ii) Small dB drops from maximum echo amplitude, such as -3 dB, were often of the same order as coupling variations experienced due to small surface contour changes. Reflectors were always considerably undersized.

(iii) Medium dB drops from maximum echo amplitude, such as -6 dB, while expected to produce the most accurate results (based upon theory), often tended to undersize the reflector. The reasons for this appear to be:

(a) Many of the real and artificial flaws produce indications with two or more peaks in the length signature. The amplitude dip between the peaks often exceeds 6 dB and a single flaw of large length could erroneously be recorded as separate multiple flaws of short length. This effect is observed in field inspections, particularly with extended flaws such as slag lines and lack of penetration.

(b) When determining maximum echo amplitude, the inspector has freedom to manipulate the search unit. When measuring length, the inspector is denied this freedom. In order to obtain correct position values for reflector end points, it is important that the search unit be moved laterally as parallel as possible to the line of reflector with minimal search unit manipulation. However, the search unit glides over surface contour undulations which can cause variations in coupling and unintended changes in search unit orientation, which in turn effects the amplitude of the reflector echo peaks.

(c) Even with care, it is easy to wander off the line of the reflector or to subtly vary the orientation of the search unit during length measurement. Thus, the sound beam strikes a different area of the reflector and the amplitude of the reflector echo peaks changes by a few or several dB. Repeated length signatures of artificial and real flaws showed that the first three dB or so of an echo's amplitude envelope is questionable in terms of repeatability. The lower portion of the signature envelope (greater than twelve dB below the peak) is least affected.

(iv) Medium dB drops from maximum echo amplitude, such as -12 and -14 dB were found to be reasonably accurate but the 14 dB drop method is much preferred because of its ability to measure the width of the main echo envelope as opposed to the width of a single peak within the envelope.

(v) Large dB drops from maximum echo amplitude, such as -20 dB, tended to oversize the artificial flaws produced from rectangular EDM slots. The 20 dB drop method was the most accurate method for measuring the lengths of artificial flaws produced from hemi-elliptical saw cuts. However, it should be noted that the artificial flaws used in this study exhibited quite high amplitude indications, from -2 dB to +14 dB in relation to DAC and little difficulty was encountered in identifying the flaw end points, 20 dB below maximum amplitude.

Both the -14 dB and -20 dB drop methods gave reasonably accurate lengths for real weld flaws. The real flaws used in this study, exhibited indications ranging in amplitude from -14 dB to +2 dB in relation to DAC. At amplitudes below DAC, it was sometimes difficult to determine clearly the 20 dB down flaw end points due to the presence of low amplitude signals (nonrecordable level) coming from other small discontinuities present in the inspection area. As a result, the 20 dB drop method frequently oversized true flaw length by a large margin.

(vi) ASME decibel drop techniques (drop to 100% DAC and drop to 50% DAC) varied greatly in their ability to measure accurately reflector length. The problem is that the amount of signal drop from maximum amplitude to a fixed threshold level, such as 100% DAC or 50% DAC, varies with the value of maximum amplitude. For example, with a threshold of 50% DAC, a +4 dB indication would drop 10 dB and exhibit a large length, a -4 dB indication would drop 2 dB and exhibit a short length while any indication at or below -6 dB would have no recordable length.

There is fundamental difference between measuring size by a fixed dB drop from maximum echo amplitude and the ASME method of a variable dB drop from maximum echo amplitude to a fixed percentage of DAC.

It is interesting to note that the maximum amplitude of indications from flaws recorded in the inservice inspection of Canadian nuclear plants seldom exceeds +6 dB. Assume that a decibel drop of 14 to 20 dB is required to measure accurately the length of a real weld flaw. Use of the ASME procedure for determining length at 50% DAC would result in a maximum dB drop of 12 dB while ASME drop to 100% DAC would result in a maximum dB drop of only 6 dB. Thus, the ASME equivalent dB drop is insufficient for flaws of amplitude +6 or lower and measured ultrasonic lengths would be consistently smaller than the actual flaw length.

(vii) A few of the artificial flaws were considerably oversized by the techniques of 12 to 20 dB drop from maximum echo amplitude. In most cases, this phenomenon was found to be due to the presence of at least two separated, high-amplitude reflecting areas in a single flaw.

As the search unit is moved laterally to determine flaw length, two overlapping echo envelopes occur, one from each high amplitude reflecting area. The width of the resultant echo envelope is considerably greater than the length of the flaw, especially if the high amplitude reflecting areas are located at the ends of the flaw. Observed on the flaw detector screen; as a search unit begins to detect the flaw, the echo amplitude of the first reflector rises from zero, reaches a maximum and then decreases. At some point during this decrease, the echo amplitude from the second reflector begins to rise from zero and increase towards its maximum amplitude. As the scan is continued, the decrease of the first echo is stopped by the increase of the second and the resultant echo rises to a second peak. Finally, the echo decreases to zero and the scan is over. These echoes occur close together and merge during the scan so that separation is difficult.

This phenomenon tends to occur when the search unit angle is such that the sound beam does not strike the flaw at a favourable angle (not normal incidence). The effect is most pronounced with planar flaws where most of the sound striking the plane reflecting area is reflected away from the search unit. Only the ends of the flaw radiate sound over a wide enough angle to return to the search unit. Ultrasonically, this type of flaw behaves in a manner similar to two small reflectors located at each end of the flaw. If the beam width at the flaw is smaller than the end point separation, then two separate echo envelopes occur, each the width of the sound beam at the flaw. If the beam width is greater than the end point separation, then the two echo envelopes overlap producing a single extended echo envelope with two peaks. The larger dB drop techniques such as -14 dB and -20 dB are better for accurately measuring the total length of such merged envelopes but over sizing may still result.

To distinguish a single flaw, twin echo peak condition, from two closely spaced but separated flaws, it is beneficial to inspect with a search angle such that the sound beam strikes the flaw at near normal incidence. A single flaw will produce a stronger reflected signal with one major peak in its echo envelope. The two separated, but closely spaced flaws, will continue to produce an echo envelope with two peaks.

The corollary is quite disturbing. It would appear possible that a large, vertically oriented, planar flaw could be misinterpreted as two small, widely spaced, low amplitude (perhaps not recordable) flaws.

(viii) In certain cases it was observed that the ultrasonic length of the reflector was correct but the length signature envelope or plotted reflector location appeared to be shifted relative to the actual reflector location. This phenomenon is similar to periodic inspection records documenting apparent changes in a reflector's location with no change in length ("reflector mobility").

Reflector mobility can be caused by detecting maximum echo amplitude with the search unit not pointed exactly normal (N) to the line of the flaw, but at some yaw (Y) angle to it as shown in Figure 13. This shifts the search unit A coordinate position where maximum echo amplitude was noted. As the search unit is moved parallel to the reflector, this yaw angle is held constant (no swivel allowed) and the A coordinates of reflector end points (E1 and E2) are similarly shifted. For yaw angle incidence, the length between the end points remains the same as for normal incidence but the recorded positions are shifted. The larger the distance between the search unit and reflector, the greater is the position shift.

With manual recording, inspector error can also produce an apparent shift in the position of a reflector. A most common error, illustrated in Figure 14, is related to the practice of marking the position of the search unit upon the work piece. The correct action is to mark the position of the centre front (F) of search unit and the position of the exit point (S), visible on the side of the search unit, as shown in 1a of Figure 14. The search unit is removed from the work piece and the marks extended to locate the exact point of sound exit (E) from the search unit as shown in 1b of Figure 14. The point (E) is then recorded as search unit position in terms of A and B coordinates.

During early manual scans of the artificial flaws, the inspector had difficulty in observing the exit point on the side of the search unit. He reverted to a practice that is often employed in field inspections, particularly when physical constraints or poor lighting prevent marking or clearly viewing the centre front or side exit point of the search unit. In such a case, the inspector runs a marker along one side and along the front or back of the search unit as shown in 2a of Figure 14. The search unit is removed from the work piece and the marks extended to intersect at some point (E) as shown in 2b of Figure 14. The inspector can then convert this position to the correct point of sound exit by allowing for the distance between exit point and the back of the search unit and between the centre and side edge of the search unit as shown in 2c of Figure 14. Yet, if the inspector forgets to do this, the recorded search unit position will remain in error as shown in 2b of Figure 14. Moreover, if the inspector makes a mistake in the calculation (e.g., add instead of subtract), then a severe shift of recorded search unit position can occur as shown in 2d of Figure 14. Thus, the reflector may appear to shift position between inspections.

4. Observations on Vertical Extent Measurement Techniques

(i) Small flaws: Most of the artificial flaws examined had actual vertical extents of about 5 mm. The ultrasonic vertical extents bore little relation to the actual vertical extent of these flaws. This was true for all dB drop methods, whether by dB drop from maximum amplitude (-1, -3, -6, -12, -14, -20 dB) or drop to 100% DAC or 50% DAC.

The vertical extent signatures clearly show that no useful size information could be obtained ultrasonically. With few exceptions, the ultrasonic vertical extent was greater than the actual vertical extent of the flaw and was of the same order as the beam width at the flaw.

The reason for this is fundamental physics. Decibel drop methods cannot determine accurately the size (vertical extent in this case) of a flaw which is smaller than the width of the sound beam at the flaw. Attempts by dB drop methods to determine the size of a flaw, which is smaller than the beam width striking the flaw, will result in measuring the width of the sound beam, not the size of the flaw.

Small targets, such as side drilled holes in an IOW beam profile block, are regularly used to measure the width of the sound beam at various depths. This enables the construction of the search unit beam profile and is standard accepted practice. One should not be surprised that attempting to size a flaw that is also a small target (relative to the beam width) results in sizing the sound beam, not the flaw.

Given a flaw which is smaller than the beam width, plotting the ultrasonic vertical extent data by the beam centre line method will result in a distorted reconstruction of the beam width at the flaw. The distortion may provide some clues as to the orientation of the flaw, but provides no information on flaw dimensions. Thus, a small flaw (say 5 mm) appears as large as the sound beam width at the flaw. The greater the search unit to flaw distance (CRT distance), the larger the flaw will appear to be. The same flaw may appear to have a vertical extent of 7 mm at 2/8th of a vee path, 14 mm at 6/8th of a vee path and 21 mm at 10/8th of a vee path.

The same small flaw, plotted using the ultrasonic vertical extent data by the more complicated beam profile method, will result in a distorted three point "L" shape which is considerably smaller than the beam width at the target, but has no relation to the flaw's dimensions. With the beam profile method, the incorrect plotted dimensions of the flaw will change little with variation in search unit to flaw distance since the effect of beam spread is compensated for.

The three point "L" shape of the beam profile method originates from different reflecting areas on the flaw and small errors in recording search unit positions. With no position errors, vertical extent data from a hole in the IOW block would plot as a single point. The CRT distances and search unit positions for centre of beam, front of beam and back of beam (for the whatever dB drop in use) would each plot as a single point, all points overlapping. However, even with the IOW block, small errors in measuring search unit position or reading CRT distances will result in the plotted points spreading somewhat and the three point "L" shape will appear. Real flaws have different sound reflecting geometries and the three point spread will be greater.

The beam centre line method and the beam profile method of plotting a small flaw (smaller than the beam width at the flaw) do not provide an accurate display of flaw vertical extent or flaw orientation.

Generally, the beam centre line method will oversize a small flaw while the beam profile method will undersize the same small flaw.
Historically, one could ponder the introduction of the beam profile method as a means to reduce significantly the apparently large vertical extent of a flaw. Vertical extents often appear nearly through-wall, especially at long CRT distances (large beam spread) and the component would long since have fallen apart if these vertical extents were true. Given the choice between using beam centre line plots that produce large vertical extents or beam profile correction plots that produce small vertical extents, opting for the later has a single major advantage. A regulatory body is apt to look more favourably upon a flaw, in say a 20 mm thick component, reported as having a vertical extent of 3 mm than a flaw reported as having a vertical extent of 15 mm.

There were few cases when the artificial flaws, having an actual vertical extent of 5 mm, produced an ultrasonic vertical extent which was larger than the beam width at the flaw. Usually, this phenomena was found to be due to the presence of at least two separated, high amplitude reflecting areas in the single flaw. As the search unit is moved forward and backwards to determine flaw vertical extent, two or more overlapping echo envelopes occur. The width of the resultant envelope is considerably greater than the actual vertical extent of the flaw and greater than the beam width at the target. Observed on the flaw detector screen as a search unit begins to detect the flaw, the echo amplitude of the first reflector rises from zero, reaches a maximum and then decreases. At some point during this decrease, the echo amplitude from the second reflector begins to rise from zero and increase towards its maximum amplitude. As the scan is continued, the decrease of the first echo is stopped by the increase of the second and the resultant echo rises to a second peak. Finally, the echo decreases to zero and the scan is finished. These echoes occur close together and merge during the scan so that separation is difficult.

This multiple peak phenomenon tends to occur when the search unit angle is such that the sound beam does not strike the flaw at near normal incidence. The effect is most pronounced with planar flaws where most of the sound striking the plane reflecting area is reflected away from the search unit. Only the top and bottom ends of the flaw radiate sound over a wide enough angle to return to the search unit. Ultrasonically, this type of flaw behaves in a manner similar to two small reflectors located at the top and bottom extremities of the flaw. If the beam width at the flaw is smaller than the end point separation, then two separated echo envelopes occur, each the width of the sound beam at the flaw. If the beam width is greater than the flaw end point separation, then the two echo envelopes overlap producing a single extended echo envelope with two peaks.

(ii) Large Flaws: Test Plate #6 contained an EDM slot of actual vertical extent 60 mm angled at 60 degrees to the surface. The vertical extent of this flaw is considerably greater than the sound beam width at the target. Ultrasonic vertical extent, as determined by forward and backward movement the search unit, was measured first with a 60 degree angle beam search unit. In this case, the sound beam was at normal incidence to the flaw and the ultrasonic vertical extent was found be most accurate and repeatable when employing a decibel drop from maximum echo amplitude of 14 dB. Decibel drops less of than 14 dB undersized the reflector, the degree of under sizing being progressively more pronounced with smaller values of dB drop. Similarly, increasing the decibel drop above 14 dB progressively oversized the reflector.

In plotting the results of the 60 degree scan (normal incidence on the flaw), the method of beam centre line was found to be most accurate for producing both correct vertical extent and orientation of the flaw. Plotting by the beam profile method caused little change in orientation but significantly undersized the actual vertical extent of the flaw.

When this same large vertical extent flaw was scanned with a 45 degree search unit, two widely spaced ultrasonic indications were obtained. The first corresponding to the top end of the flaw and the second to the bottom end. Each indication exhibited a vertical extent similar to the sound beam width at the CRT distance to the top or bottom end of the flaw respectively. This phenomenon is the same as that described three paragraphs above. The 45 degree search unit angle produces a sound beam which does not strike the flaw at normal incidence (as 60 degree did). The planar flaw reflects most the sound away from the search unit. Only the top and bottom ends of the flaw radiate sound over a wide enough angle to return to the search unit. In this case, the beam width at the flaw is smaller than the end point separation, and two separated echo envelopes occur, each the width of the sound beam at the flaw. The most correct orientation and vertical extent results from simply plotting the centre line position of the two peaks, not by a dB drop method.

5. Observations on Sizing Repeatability

The following sections examine sizing repeatability of decibel drop methods, ultrasonic equipment and ultrasonic inspectors.

5.1 Decibel Drop Methods - Repeatability

The sizing repeatability of a given dB drop method for repetitive examination of a chosen flaw was studied by repeating scans of flaw length signatures over periods several days apart. Review of these signatures indicated that with correctly maintained search unit orientation, the amplitude of all echo peaks within the flaw length signatures were repeatable within + or - 3 dB and the position of the peaks and valleys were repeatable to within + or - 2 mm.

With alterations in search unit orientation, the length signatures changed; peaks altered considerably in amplitude (several dB) but little in position (+ or - 2 mm). While the internal details of the signature changed, the overall envelope remained relatively unchanged. The ultrasonic flaw lengths measured by small dB drops such as -3 and -6 dB were quite sensitive to the internal details and changed greatly. Ultrasonic flaw lengths determined by larger dB drops such as -14 and -20 dB measured only the width of the overall envelope and changed only slightly (+ or - 2 mm). These results indicate that repeatability of flaw sizing, irrespective of accuracy, will be better for the larger decibel drop methods such as -14 and -20 dB as compared to the smaller decibel drop methods such as -3 or -6 dB.

In terms of mathematical repeatability of size, the 20 dB drop method gave the most repeatable results but this result is somewhat misleading. The same sizing error will appear as a smaller variation with larger dB drop methods simply because they generally yield larger flaw sizes. For example, a sizing error of 4 mm in the 20 mm reported length of a flaw as measured by the 6 dB drop method appears as a 20% variation. Yet, the same sizing error of 4 mm in the 40 mm reported length of the same flaw as measured by the 20 dB drop method appears as only a 10% variation.

Repeatability of the decibel drop sizing methods cannot be considered in isolation of accuracy; the ability to yield accurate flaw size. The inspection philosophy exemplified by the statement "**If it's not accurate, at least it's reproducible.**" is erroneous. This study has clearly shown that one can size flaws smaller than the sound beam width achieve repeatable sizes that have no relationship to the flaw dimensions, but are in fact a measure of the sound beam width. In a similar way, the ability of the 20 dB drop method to appear repeatable must be weighed against it frequent tendency greatly oversize a flaw in the presence of other small discontinuities. One must strive to achieve "repeatable, accurate sizing".

5.2 Ultrasonic Equipment - Repeatability

In order to maintain the highest degree of confidence in comparing the sizing results of various decibel drop methods, RPC purposely chose to use a single flaw detector and single transducer (equipped with three interchangeable angle beam wedges) throughout the duration of the project. As a result, the effects of changes in equipment such as different flaw detectors, search units, etc. on sizing repeatability was not directly addressed in this study.

However, for sizing of flaws by decibel drop methods, this study has shown the importance of the relationship between sound beam parameters (beam width and beam incidence angle) and flaw parameters (size and orientation). While one has no control over flaw parameters, the sound beam parameters must be carefully chosen, monitored and controlled if repeatable sizing is to be obtained. The manner of choosing the proper combination of ultrasonic instrument and search unit for the work pieces to be inspected and incorporating such selections into a written procedure is a complex matter, considered beyond the scope of this study. Monitoring of sound beam parameters can be performed through proper instrument/search unit calibration and continued verification checks. Monitoring techniques should form an essential part of written inspection procedures. Control of beam parameters can be maintained through acceptance/rejection criteria on the monitoring techniques. Specific recommendations for monitoring and control of sound beam parameters are presented in section G, Recommendations.

5.3 Ultrasonic Inspector - Repeatability

Ultrasonic inspectors do make mistakes which affect both the accuracy and repeatability of flaw sizing. Section 3.4 gave an example where an inspector mistake (improper marking practice) produced an apparent shift in the recorded position of a flaw. The flaw length was repeatable but its position was not.

In this study, manual scans of flaw size at selected decibel levels did not deliver the detail necessary to reveal why certain phenomena were occurring. In a move to gather a larger volume of more detailed data, an experienced ultrasonic technician was provided with a mechanical/electronic data logger. This freed the inspector from having to laboriously fill in detailed forms. The inspector had only to note the important parameters such as search unit angle, maximum amplitude, CRT distance and search unit A and B coordinates at maximum amplitude position on the graph produced by the data logger. Fully one tenth of the approximately 200 scans had to be repeated because of missing parameters or questionable parameter values. The ultrasonic inspector freed from a "fill in the blank recording form" forgot to enter essential data. This demonstrates the need for written inspection procedures and field work forms. Suggestions for reducing ultrasonic inspector errors are presented in section G, Recommendations.

E. GENERAL CONCLUSIONS

1. Report Conclusions Based Upon Report Observations

(i) Decibel drop methods of sizing, for either length or vertical extent, produce accurate results only when the flaw dimension being measured is larger that the sound beam width striking the flaw.

Decibel drop methods cannot determine accurately the length or vertical extent of a flaw when the dimension being measured is smaller than the width of the sound beam at the flaw. Attempts by dB drop methods to determine the length or vertical extent of a flaw, which is smaller than the beam width striking the flaw, will result in measuring the width of the sound beam, not the dimensions of the flaw.

For flaws of actual vertical extent less than the sound beam width, the ultrasonic vertical extent will be erroneous and equal to the width of the sound beam striking the flaw. Plotting of this erroneous data by beam centre line displays an oversized flaw. Plotting of this erroneous data by the beam profile method displays an undersized flaw. Neither plotting method displays the true flaw vertical extent or orientation.

(ii) For real weld flaws, having dimensions larger than the sound beam, decibel drop methods of 14 to 20 dB appear to give the most accurate assessment of length. This compares with the 14 dB and 20 dB drops for accurate length measurement of EDM slots and hemi-elliptical saw cuts respectively. For real weld flaws, general implementation of 20 dB drop method for assessing flaw length does not appear practical because of the tendency of very small discontinuities in a "dirty" weld to contribute to the echo envelope and extend the apparent length of the flaw. It is recommended that the dB drop method based on a 14 dB drop from maximized indication amplitude be used to assess flaw length.

Based on sizing a single artificial flaw of large vertical extent, the dB drop method of 14 dB appears to give the most accurate results. Plotting of vertical extent by the beam centre line method yields the most accurate display of flaw vertical extent and orientation. Plotting by beam profile methods displays vertical extents which are considerably smaller than the actual vertical extent of the flaws. It is recommended that vertical extent be plotted by the beam centre line method.

For large planar flaws, decibel drop methods work best when the sound beam is directed to strike the flaw at normal incidence. Since the orientation of the flaw is unknown, several angles should be used.

F. IMPLICATIONS FOR INSERVICE INSPECTION

1. Comments on Current Field Practice

The results of this study can be used to assess the current capabilities, limitations and the past results of Canadian nuclear inservice inspections.

1.1 Flaw Length

The search unit most commonly employed for inservice inspection of piping systems is of 12.7 mm diameter, 2.25 MHz operating frequency and of 70, 60 and 45 degree angles. For these search units, the minimum sound beam width occurs at or near the search unit/part interface, the sound beam expanding as it travels further into the part. The 6 dB minimum beam widths are about 8 mm and the 12 dB and 20 dB minimum beam widths are greater than this 8 mm value. Many utilities employ these same search units for vessel inspection and the following comments would also apply to vessel inspection. Other search units of different diameter or frequency will exhibit different values of minimum beam width, but the following logic is applicable to all inspections.

At present, flaw length is plotted using centre line plotting techniques (no beam profile correction). As a result, the smallest recorded flaw length will correspond to the beam width at the flaw. Since the minimum beam width of a 12.7 mm, 2.25 MHz search unit is about 8 mm, it is expected that the minimum length recorded for any flaw detected in pipe has been about 8 mm.

For flaws of large length (larger than the beam width at the flaw), this study has shown that a decibel drop of about 14 dB is required to determine accurately flaw length. Thus, for flaws in both pipe and vessels, the reported lengths of flaws which are larger than the beam width will be reasonably correct if they were sized by 14 dB drop. If sized by a lesser dB drop, such as -6 dB, flaws will have been erroneously recorded as shorter than their actual length or appear as a number of short, closely spaced flaws.

1.2 Flaw Vertical Extent and Orientation

For dB drop methods, this study has shown that no useful data on flaw vertical extent or flaw orientation can be obtained when the flaw dimensions are less than the beam width. The majority of flaws in piping and vessels are in this category, the flaws having vertical dimensions smaller the beam width (8 mm minimum at 6 dB drop for a 12.7 mm, 2.25 MHz search unit). Therefore, it is expected that the vertical extent and orientations of the majority of flaws in pipe and vessels, measured by dB drop methods, have been erroneously reported.

2. Comments on CSA Standard and ASME Code Requirements (1983)

The following sections compare CAN3-N285.4-M83 with ASME Sections V and XI. The code implication of limitations in dB drop sizing methods are discussed.

2.1 Review of CAN3-N285.4-M83

In reference to indications in the weld zone CAN3-N285.4-M83 states:

Inaugural Inspection:
- Recordable indication; amplitude greater than 20% DAC.
- Amplitude greater than 100% DAC; record location, dimensions, amplitude, orientation, type and then evaluate per Clause 8.1 of CAN3-N285.4-M83.
- Amplitude greater than 50% DAC and less than or equal to 100% DAC; record location, dimensions, amplitude, orientation and then accept.
- Amplitude greater than or equal to 20% DAC and less than or equal to 50% DAC; record amplitude, location and then accept.

Periodic Inspection:
- Recordable indication; amplitude>100% DAC.
- Determine location, dimensions, orientation and type.
- If orientation normal (+ or - 60 degrees) to the surface then evaluate acceptability per ASME Section XI, IWB-3500.
    - If acceptable, then accept.
    - If not acceptable, evaluate by analysis per ASME Section XI, Appendix A; BS-PD6493 or other accepted method. If acceptable, then accept. If not acceptable, evaluate and dispose per Clause 8.1.3, CAN3-N285.4-M83.
- If orientation is parallel (+ or - 30 degrees) to the surface then the maximum acceptable length 'A' of the indication determines what happens. The value of A varies with thickness 'T'; A=6 mm for T<20 mm, A=T/3 for 20 mm<T<60 mm and A=20 mm for T>60 mm.
- If the indication length is less than or equal to A, then the indication is acceptable.
- If the indication length is greater than A then acceptability per ASME Section XI, IWB-3500.
    - If acceptable, then accept.
    - If not acceptable, evaluate by analysis per ASME Section XI, Appendix A; BS-PD6493 or other accepted method. If acceptable, then accept. If not acceptable, evaluate and dispose per Clause 8.1.3, CAN3-N285.4-M83.

Standard CAN3-N285.4-M83, Clause 4.2, Procedures, states that "the procedures shall comply with the requirements of the ASME Boiler and Pressure Vessel Code, Section V".

In summary, CAN3-N285.4-M83 initially determines what to do with a weld zone indication based upon the its maximum amplitude relative to thresholds set at 100%, 50% and 20% of DAC. Inaugural inspection requires recording of dimensions and orientation if the maximum amplitude exceeds 50% DAC. Periodic inspection requires recording of dimensions and orientation if the maximum amplitude exceeds 100% DAC. Indications within the weld zone which are either oriented within + or - 60 degrees of normal or are greater in length than the maximum acceptable length 'A' are evaluated for acceptability in accordance with ASME Section XI, IWB-3500. Indications, which are found to be unacceptable to IWB-3500, must have their acceptability evaluated by analysis in accordance with ASME Section XI, Appendix A; BS-PD6493. The standard requires ultrasonic procedures in accordance with ASME Section V.

2.2 Review of ASME Section V (1983)

2.2.1 Article 4, Ultrasonic Examination Methods for ISI

T-441 Vessel Examinations, paragraph T-441.3.2.8:

- "Record all reflectors that produce a response equal to or greater than 50% of the distance-amplitude correction (DAC)."
- "Record data for the end points as determined by 50% of DAC. Emphasis must be placed on measurement of the parameters determining the reflector length and height and the distances from the examining surface to the top and bottom of the reflector, since these dimensions are the factors most critical in determining ultimate evaluation and disposition of the flaw"
- "The following data shall be recorded when a reflector exceeds 50% DAC.
  - (1) Maximum percent of DAC, sweep reading of indication, search unit position, location along the length of the weld, and beam direction.
  - (2) **Through-Wall Dimension**
    - (a) For reflectors 50 to 100% DAC, the minimum sweep reading and its position and location along the length of the reflector for 50% DAC when approaching from the maximum signal direction.
    - (b) For reflectors 50 to 100% DAC, the maximum sweep reading and its position and location along the length of the reflector for 50% DAC when moving away from the reflector's maximum signal direction.
    - (c) For reflectors exceeding 100% DAC, minimum sweep reading and its position and location along the length of the reflector for 50% of the maximum amplitude when approaching the reflector from the maximum signal direction.
    - (d) For reflectors exceeding 100% DAC, maximum sweep reading and its position and location along the length of the reflector for 50% of the maximum amplitude when moving away from the reflector's maximum signal direction.
  - (3) **Length Dimension**
    The length of the reflector shall be obtained by recording the position and location along the length of the weld as determined by 50% of DAC for each end of the reflector."

To summarize, Section V, Article 4 of ASME 1983 requires recording of an indication if its maximum amplitude equals or exceeds 50% DAC. Length is determined (by moving the search unit along the length of the weld) at the end points of the reflector where the indication's amplitude decreases to 50% DAC. Through-wall dimension, hereafter referred to as vertical extent, is determined (by moving the search unit towards and away from the weld, in a direction usually normal to the weld). For reflectors of amplitude between 50% DAC and 100% DAC, vertical extent is determined at the end points of the reflector where the indication's amplitude decreases to 50% DAC. For reflectors of amplitude greater than 100% DAC, vertical extent is determined at end points of the reflector where the indication's amplitude decreases to 50% of maximum amplitude (the same as 6 dB drop from maximum amplitude).

2.3 Review of ASME Section XI (1983)

2.3.1 IWB-3500 Acceptance Standards

IWB-3500 sets limits on the allowable ratio of planar flaw through-wall dimension 'a' or '2a' to material wall thickness 't' based upon the flaw aspect ratio 'a/l' (flaw through-wall dimension 'a' or '2a' to flaw length 'l'). For surface flaws, the through-wall dimension is taken as 'a' while for sub surface flaws, the through-wall dimension is taken as '2a'. Various tables provides these limits for planar, laminar and linear flaws in the welds in ferritic steel, welds of nozzles in vessels, ferritic piping, bolting and vessel, piping, valve and pump attachments, pump casings, etc.

2.3.2 ASME XI - Appendix A Analysis of Flaws

Appendix A uses specific data related to flaw through-wall dimension 'a' or '2a', length 'l' and orientation in order to calculate the acceptability of the flaw based upon an analytical model for linear elastic fracture mechanics.

2.4 Comments on ASME References in CAN3-N285.4-M83

CAN3-N285.4-M83 states that procedures shall comply with the requirements of ASME Section V and that ASME Section XI, IWB-3500 and Appendix A shall be used for determining the acceptability of ultrasonic indications. Yet, Section XI acceptability criteria are based upon Section XI procedures not Section V's.

Section XI, IWA-2232 Ultrasonic Examination states; "Ultrasonic examination of vessel welds in ferritic material greater than 2 inches in thickness shall be conducted in accordance with Article 4 of Section V amended as follows." The amendments do not alter the Section V sizing methods. Thus, for vessel welds over 50.8 mm thick the sizing requirements are the same in Section XI and V.

ASME Section XI, Article IWA-2000, paragraph (b) of IWA-2232 Ultrasonic Examination states; "Ultrasonic examination of piping systems shall be conducted in accordance with Appendix III." ASME Section XI, Appendix III, Ultrasonic Examination of Piping Systems, III-4520, Recorded Data, states that data shall be recorded on "(b) search unit positions parallel to the reflector end points where reflector amplitude equals 50% of the peak amplitude (estimated length);". Thus, piping examination is different from Article 5 of ASME Section V and data recording is different from Article 4 of Section V, which requires length determination at 50% of DAC.

ASME Section XI, Article IWA-2000, paragraph (d) of IWA-2232 Ultrasonic Examination states; If the requirements of (a) [vessel welds in ferritic material greater than 2 inches thick], (b) [piping systems] or (c) [bolts and studs] above are not applicable, the ultrasonic examination shall be conducted in accordance with the applicable requirements of Article 5 of Section V, amended as follows.

(3) The size of reflectors shall be measured between points that give amplitudes equal to 100% of the reference level.

Item (3) above is a different from Article 4 of Section V which requires length determination at 50% DAC and through-wall dimensions measurements at either 50% of DAC (reflector amplitude between 50% and 100% DAC) or 50% of maximum amplitude (reflector amplitude greater than 100% DAC).

To summarize the differences between ASME Section V and Section XI, one has:

	ASME SECTION V	ASME SECTION XI
Pressure vessels weld of thickness greater than 50.8 mm		
length	50% DAC	50% DAC
vertical extent	50% DAC (ampl.=50% to 100%) -6 dB drop (ampl.>100%)	50% DAC (ampl.=50% to 100%) -6 dB drop (ampl.>100%)
Pressure vessel welds of thickness less than or equal to 50.8 mm		
length	50% DAC	100% DAC
vertical extent	50% DAC (ampl.=50% to 100%) -6 dB drop (ampl.>100%)	100% DAC 100% DAC
Piping systems		
length	50% DAC	-6 dB drop
vertical extent	50% DAC (ampl.=50% to 100%) -6 dB drop (ampl.>100%)	50% DAC (ampl.=50% to 100%) -6 dB drop (ampl.>100%)

2.4.1 Inappropriate Use of ASME Codes in CAN3-N285.4-M83

For thin pressure vessel welds and piping systems, the present CSA standard CAN3-N285.4-M83 requires the assessment of an ultrasonic indication to Section XI acceptance/rejection criteria even though the indication's length and through-wall dimension were measured by methods clearly in violation of the Section XI procedures for measuring length and through-wall dimension. It is a recommendation of this report that this incompatibility be addressed.

ASME Section XI acceptance/rejection criteria are highly detailed for various types of components, wall thickness and service conditions. The nature of the flaw (planar/nonplanar, laminar, linear, etc.), its length, through-wall dimension and proximity to the surface are all considered in the final assessment. It is reasonable to expect that any major deviation from the Section XI procedural requirements for measuring length and through-wall dimensions would cause an invalid assessment.

The Canadian CSA standard CAN3-N285.4-M83 in attempting alignment with the American ASME Codes appears to be somewhat incompatible with ASME Sections III, V and XI. The CSA standard requires ultrasonic procedures in accordance with ASME Section V. Yet, while ASME Section V looks to ASME Section III for acceptance/rejection criteria, the CSA standard refers to ASME Section XI for acceptance/rejection criteria. The problem is that ASME Section XI acceptance/rejection criteria are based upon Section XI size measurements techniques for length and through-wall dimensions, not those of Section V. **ASME Section V and XI measurement techniques are only the same for thick (greater than 50.8 mm) pressure vessel welds and are very different for both thinner pressure vessel welds and piping systems.**

2.5 Limitations of dB drop Sizing Methods Verses Codes Requirements

2.5.1 ASME 100% DAC and 50% DAC Threshold

This study has clearly shown that the ASME methods of dropping an indication from maximum amplitude to a fixed threshold, either 100% DAC or 50% DAC, do not give accurate nor repeatable sizes. By comparison, a given decibel drop method such as -14 dB may not always give the correct flaw size but at least it will tend to either consistently undersize or oversize most recordable flaws, irrespective of the ultrasonic echo amplitude of the flaws. This is not true of the ASME fixed threshold methods where a flaw of large ultrasonic amplitude will almost always exhibit a much greater size than a flaw of low amplitude. The ASME ultrasonic procedures which require dropping a maximized indication to 100% DAC or 50% DAC has no justification either in theory or in documented experimental results and have demonstrated the most inconsistent sizing results of all dB drop methods. Their use is highly discouraged.

2.5.2 Flaw Orientation and CSA Standard CAN3-N285.4-M83

CAN3-N285.4-M83 requires for inservice inspection that all indications having amplitude greater than 100% DAC be ultrasonically evaluated to determine if the flaw is orientated normal (+ or - 60 degrees) to the surface or parallel (+ or - 30 degrees) to the surface.

This study has shown that if the flaw has an actual vertical extent greater than the sound beam width at the flaw, the displayed flaw orientation will be reasonably correct if plotted by either the beam centre line method or the beam profile method using dB drops up to about -14 dB. However, when a flaw has an actual vertical extent less than the beam width at the flaw, flaw orientation cannot be determined by dB drop methods. The great majority of flaws detected in Canadian nuclear components are in this later category and the orientation determined by the dB drop methods is erroneous. Thus, for the majority of flaws, the CAN3-N285.4-M83 requirement to determine flaw orientation cannot be met using the present dB drop sizing techniques.

2.5.3 Flaw Length in Respect of CSA Standard CAN3-N285.4-M83

CAN3-N285.4-M83 requires for inservice inspection that all indications having amplitude greater than 100% DAC and oriented parallel (+ or - 30 degrees) to the surface be evaluated for length and assessed against the term 'A'. The term A = 6 mm for material up to 20 mm in thickness (T), A = T/3 for material from 20 mm to 60 mm thick and A = 20 mm for material over 60 mm thick.

Most CANDU pipe requiring inspection is in the thickness range 18 mm through 27 mm. According to the CSA standard, the ultrasonic sizing method must be able to correctly determine length of pipe flaws in the range 6 mm to 9 mm. This is of the same order as the minimum 6 dB sound beam width (i.e., about 8 mm near the search unit/part interface surface or at short CRT distances) from standard 12.7 mm, 2.25 MHz angle beam search units presently in use. As a result, the minimum reported length of a pipe flaw will be about 8 mm and can easily exceed this value if shot from a longer CRT distance. The present dB drop sizing methods, applied using the current search units, are just not capable of accurately sizing flaws below about 8 mm in length. Therefore, almost all flaws, irrespective of their actual size, will produce a CSA standard 'A' value greater than the standard allows for acceptance. At present, it appears that no accurate assessment can be made by decibel drop sizing methods to determine if the flaw length meets or fails the CSA standard's 'A' term criteria.

G. RECOMMENDATIONS

The following recommendations are based upon the results, observations and conclusions of this report. While the evidence gathered during this project points the way, it should be cautioned that the implementation of these recommendations should be considered in conjunction with further laboratory evaluation of real weld defects, particularly service flaws, and with on site field trials to ensure the practical feasibility of the recommendations.

1. Specific Parameters for Written Procedures

For sizing of flaws by decibel drop methods, the study has shown the importance of the relationship between sound beam parameters (beam width and beam incidence angle) and flaw parameters (size and orientation). The sound beam parameters must be carefully chosen, monitored and controlled if accurate and repeatable sizing is to be obtained. Careful consideration must be given to the decibel drop method to be used, the equipment and inspectors.

1.1 Sound Beam Width

Beam width diagrams should be used during scanning as reference guides to judge whether or not the dimensions of ultrasonic indication are greater than the ultrasonic beam width at the flaw. At present, beam width diagrams are produced only in the vertical plane for assessing the vertical extent of an indication. Beam width diagrams are also needed in the horizontal plane for assessing the length of an indication. The width of the ultrasonic beam, in both planes, for the dB drop method in use, should be given much greater emphasis during actual scanning to gauge the ability of the dB drop method to accurately size an indication.

During scanning, if an indication's length appears to be greater that the horizontal beam width at the flaw, then an accurate measurement of flaw length can be made using the dB drop technique recommended in this report. If an indication's length appears smaller or of the same order as the horizontal beam width at the flaw, dB drop methods should not be used and recourse must be made to alternative techniques to measure flaw length.

During scanning, if an indication's vertical extent appears to be greater that the vertical beam width at the flaw, then an accurate measurement of flaw vertical extent and orientation can be made using the dB drop technique recommended in this report. If an indication's vertical extent appears smaller or of the same order as the vertical beam width at the flaw, dB drop methods should not be used and recourse must be made to alternative techniques for determining flaw vertical extent and orientation.

1.2 Flaw Length

Indication length should be measured by moving the search unit left and right, parallel to the length of the flaw, until the maximized amplitude of the flaw indication decreases by 14 decibels, i.e., 14 dB drop method. Plotting of the flaw ends should be done using the centre line of the beam and not with a beam spread diagram. This procedure is only valid for indications of length greater than the horizontal beam width at the flaw.

1.2.1 Monitoring Flaw Length Signature

This study has demonstrated that each flaw exhibits a unique length signature of amplitude verses search unit position. Small changes in the morphology of a flaw tend to show up quite clearly in the length signature. This can be applied for long term monitoring to detect any change in a critical flaw. RPC introduced this monitoring method during the 1983 inaugural inspection of Wolsung 1 NPP. (Korea) and three flaws have been actively monitored by this signature comparison technique during the three past inservice inspections.

Monitoring of flaw length signatures is particularly applicable to flaws exhibiting intermittent short lengths over an extensive distance, such as long slag lines or suspected cracking about nozzle welds. A complete record should be made of indication amplitude (A coordinate, B coordinate and CRT) verses search unit position as the search unit is moved in small steps (about 10 mm) parallel to the length of the flaw. Care should be taken to record positions where the flaw indication exhibits amplitude peaks and valleys. Mapping of the length signature of the indication should continue until the indication experiences its final 20 dB drop below maximum amplitude at both ends of the flaw. Signature plots of the flaw length envelope should be made to a common scale to facilitate comparison of signatures between inservice inspections.

1.3 Flaw Vertical Extent

Indication vertical extent should be measured by moving the search unit forward and backward, at right angles to the length of the flaw, until the maximized amplitude of the flaw indication decreases by 14 decibels, i.e., 14 dB drop method. Plotting of the flaw ends to determine flaw vertical extent and orientation should be done using the centre line of the beam and not with a beam spread diagram. This procedure is only valid for indications of vertical extent greater than the vertical beam width at the flaw.

1.4 Monitoring Sound Beam Parameters

Monitoring of sound beam parameters should form an essential part of the written inspection procedures. Such monitoring can be performed through proper instrument/search unit calibration and continued verification checks. The sound beam parameters of frequency, beam width and intensity distribution along and across the beam should be recorded upon receipt of a new search unit and verified yearly. Any significant change in performance characteristics of the search unit/instrument combination can be detected by daily monitoring. Monitoring can consist of recording search unit index point, operating angle and functional power on an IIW block and recording the DAC curve from the basic block in use. Control of sound beam parameters is achieved by setting acceptance/rejection limits on the recorded results of daily monitoring.

1.5 Ultrasonic Equipment

Choice of an ultrasonic search unit featuring sound beam parameters suited for inspecting the work piece is very important. An example of a poor choice is the 12.7 mm, 2.25 MHz longitudinal wave search unit currently in use for straight beam examination of pipe. This search unit lacks the resolution necessary to confirm the presence or accurately determine the location of the top of many flaws that have been detected with angle beam search units. Its near surface resolution and its ability to examine the root of the weld is inadequate due to its long near field and long acoustic wavelength (2.6 mm longitudinal as opposed to 1.4 mm for angled shear waves). It recommended that this search unit be replaced by a smaller, higher frequency unit such as a 6 or 9 mm diameter, 5 MHz unit. The simple replacement of this longitudinal search unit could provide a considerable improvement in our present ability to detect flaws in the root of the weld, to determine the nature of flaws and accurately assess the minimum flaw depth below the inspection surface.

1.5.1 Computer Assessment and Plotting

During the recording of the various flaws studied in this project many inspector errors were made. These included omitting or incorrectly recording maximum amplitude, search unit A or B coordinate and CRT distance. Incorrect values often became evident only upon plotting the indications. As a result, several time consuming rescans were required. RPC has observed such errors in field inspections, including the laborious recording of indications that are found to plot outside the weld zone. Such errors could be detected and avoided at time and place of inspection by providing the inspector with an inexpensive, light weight, battery powered, graphic microcomputer (e.g., $800 Radio Shack TRS-80 Model 100) that has been programmed for the search unit angles in use and the weld contours to be inspected.

1.6 Ultrasonic Inspectors/Procedures

This study has demonstrated that ultrasonic inspectors do make mistakes which affect both the accuracy and repeatability of flaw sizing. Sensible and clearly written inspection procedures and proper report forms can help reduce operator errors. Some examples may help to illustrate this.

Many inspection procedures require that a "transfer value" be measured to ensure that the work piece and calibration block in use are acoustically similar. Field measurement of a transfer value is time consuming, difficult to repeat due to coupling variations caused by surface contour irregularities of the work piece, and requires the simultaneous use of two search units with unusual settings of the instrument pitch/catch and time base controls. Several utilities use calibration blocks which are actual offcuts of the same material and thickness as the work piece. When using such "basic blocks" at the same temperature as the work piece, carefully measured transfer values are zero. Inspectors know this from experience. They can save time and avoid the potential danger of forgetting to readjust the instrument controls by not measuring a transfer value but by simply entering a zero value in the report form. Inspectors know this is contrary to the procedure, but feel the procedure is not "sensible". Unfortunately, inspectors having formed a habit of not measuring known zero transfer values tend to continue the practice even when a calibration block of the same thickness and material as the work piece is not available.

Some procedures are not clear or lack illustrative examples of what to do. The same uncertainties are argued over by ultrasonic inspectors from one inservice inspection to the next; "Is movement of the search unit towards the weld recorded as a plus or minus value ?", "There's nothing in the procedure on how to record an intermittent indication. Do I record all 6 dB lengths or just the last ones at each end the flaw ?", "On a nozzle weld, do I measure from the left or right B coordinate sector line and do I measure in a straight line or along the curved shell of the vessel ?". Ambiguous inspection procedures indirectly cause inspectors to perform measurements differently and the result is a lack of repeatability in recorded flaw positions and sizes.

Some report forms lack reserved space for recording important information. For example, few forms include a clearly identified space for a proper "top view" sketch of the relative position and orientation of search unit, weld centre lines and the A coordinate and B coordinate reference lines. Such a sketch would remove inspector "guess work" during plotting or the need for an inspector to return to the inspection site to clarify the situation.

Ultrasonic inspectors should be made to read the inspection procedures and sign a paper indicating they understand them before inspection commences. Even so, there are inspectors who will continue to do things "their way".

2. Future Research

This study has shown that dB drop methods of flaw sizing are not applicable to flaws whose dimensions are smaller than the width of the ultrasonic beam which strikes the flaw. To size such flaws by ultrasonics requires other methods. It is recommended that the following suggestions and ultrasonic sizing methods be evaluated on artificial flaws, real weld flaws and tested in the field.

(i) This project dealt solely with manufacturing type flaws; e.g., slag, porosity, lack of fusion and lack of penetration. Service flaws such as fatigue cracks in the root, toe and crown areas of welds were not addressed. Information on the ability of ultrasonic techniques to size such flaws would be of value.

(ii) A study should be made of tip diffraction methods (time of flight) using a single search unit (pitch catch is not practical in the field where access in often restricted to one side of the weld) to detect the sound waves radiated over a wide angle by the flaw ends. Recording of search unit angle, position and CRT distances enables a plot to be made of the tips or ends of the flaw. The method may define the length, vertical extent and orientation of the flaw.

(iii) A study should be made of synthetic aperture methods which use many angled shots from different vee paths and from all weld accessible areas. The idea is to strike the flaw surface at as many points and from as angles as possible. A record is made of each search unit angle, position and CRT distance. This data is used to plot a reconstruction of the flaw.

(iv) A study should be made of focused contact search units to achieve very small beam widths. Small flaws may then be size by current dB drop methods because the ultrasonic beam width has been reduced below the dimensions of the flaw.

Table 1: DAC Calibration Data on Basic Block RPC1 (Electronic DAC)

Search Unit Angle	45 degrees	60 degrees	70 degrees
IIW Power (dB for 80% FSH)	32 dB	39 dB	46 dB
RPC1 Basic Block DAC Data Depth of 1.5 mm hole (mm)	% FSH	% FSH	% FSH
1	80% (31 dB)	82%	80% (32 dB)
5	73%	70%	60%
7	75%	80% (32 dB)	37%
10	76%	72%	28%
15	76%	50%	16% (80% 46 dB)
20	72%	40%	62%
25	63%	30%	43%
30	55%	23% (80% 42 dB)	40%
35	45%	65%	28%
40	40%	53%	
45	34%	40%	
50	30%	37%	
55	25%		
60	21%	(Note: % means percent of FSH)	

Table 1 presents distance amplitude correction (DAC) data for each of the three search units (45, 60 and 70 degree) used in this project. This data was obtained by ultrasonic examination of the International Institute of Welding (IIW) block and basic block RPC1.

"IIW Power (dB for 80% FSH)" presents the instument gain in decibels (dB), for each search unit, needed to place the maximized indication from the 1.5 mm diameter hole (15 mm below surface) in the IIW block at 80% of full screen height (FSH). This IIW check links the subsequent DAC measurements performed on basic block RPC1 to an international standard, the IIW block.

"RPC1 Basic Block Dac Data" presents DAC data obtained by recording the maximized ultrasonic response from each of the 1.5 mm diameter side drilled holes (1 to 60 mm deep) in the RPC1 basic block. The indication, from the hole yielding maximum echo amplitude, is set to 80% FSH and the instrument gain setting recorded in dB. At this fixed gain setting, the height of the maximized indications from the remaining holes are recorded in % FSH.

In cases where the height of the maximized indication decreases to about 20% FSH (e.g., 60 degree search unit response of 23% FSH at 39 dB gain from 30 mm deep hole) , the DAC data is extended by increasing instrument gain to set the maximized indication height at 80% FSH (e.g., 60 degree search unit response of 80% at 42 dB from 30 mm deep hole). Maximized indications from the remaining deeper holes are recorded in % FSH at the new higher gain setting.

Table 2: Statistics of Ultrasonic Length Accuracy for EDM Slots in Test Plate #1

dB drop	Flaw #	Flaw Length (L) in mm	# of Shots	Mean Error mm	Mean Error % of L	Standard Deviation mm	Standard Deviation % of L
6	1	58	21	-20	-35%	17	29%
6	3	52	17	-27	-51%	13	25%
6	4	53	24	-22	-42%	14	26%
6	5	51.5	18	-21	-41%	14	27%
12	1	58	21	- 4	- 7%	10	17%
12	3	52	17	-13	-25%	16	31%
12	4	53	24	- 2	- 4%	9	17%
12	5	51.5	18	- 6	-11%	14	27%
14	1	58	21	- 0	- 0%	4	7%
14	3	52	17	- 9	-16%	15	29%
14	4	53	24	+ 2	+ 4%	6	11%
14	5	51.5	18	+ 2	+ 4%	5	9%
20	1	58	21	+ 4	+ 8%	3	6%
20	3	52	17	+ 4	+ 7%	11	22%
20	4	53	24	+ 8	+16%	5	9%
20	5	51.5	18	+ 7	+13%	4	8%

Table 3: Statistics of Ultrasonic Length Accuracy for Hemi-elliptical Saw Cuts in Test Plate #5

dB drop	Flaw #	Flaw Length (L) in mm	# of Shots	Mean Error mm	Mean Error % of L	Standard Deviation mm	Standard Deviation % of L
6	1	39	10	-20	-51%	8	21%
6	2	36	11	-15	-41%	9	24%
12	1	39	10	- 7	-18%	8	19%
12	2	36	11	- 8	-23%	9	24%
14	1	39	10	- 4	-11%	8	20%
14	2	36	11	- 6	-18%	9	25%
20	1	39	10	+ 2	+ 4%	4	11%
20	2	36	11	- 1	- 3%	6	17%

Table 4: Ultrasonic Length Accuracy Results for Real Weld Flaws in Test Plates #10 and #12

Flaw #	Flaw Length (L) in mm	6 dB Error mm	6 dB Error % of L	12 dB Error mm	12 dB Error % of L	14 dB Error mm	14 dB Error % of L	20 dB error mm	20 dB error % of L
P10L2	53	- 41	-77%	- 20	-38%	- 17	-32%	- 1	- 2%
P10L3	108	-100	-93%	- 96	-89%	- 90	-83%	- 67	-62%
P10L5	50	- 44	-88%	- 30	-60%	- 1	- 2%	+ 13	+26%
P12L1	30	- 22	-73%	- 5	-17%	- 4	-13%	+ 20	+67%
P12L3	52	- 43	-83%	- 41	-79%	- 40	-77%	- 33	-64%
P12L4	20	- 12	-60%	- 3	-15%	- 2	-10%	+ 1	+ 5%

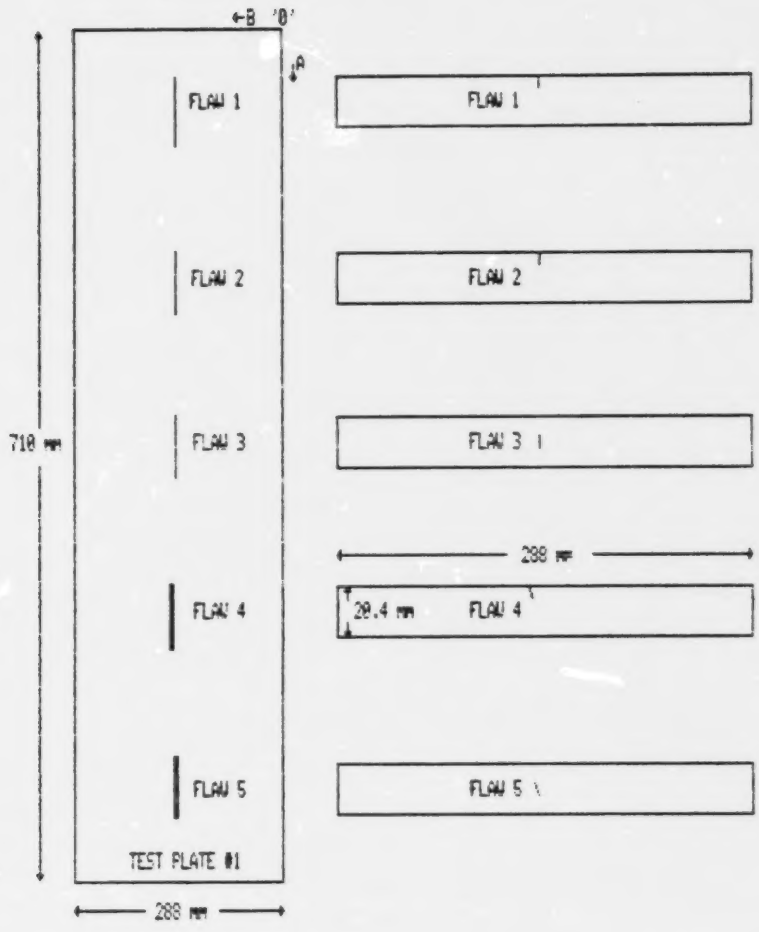


Figure 1: Illustration of Test Plate #1

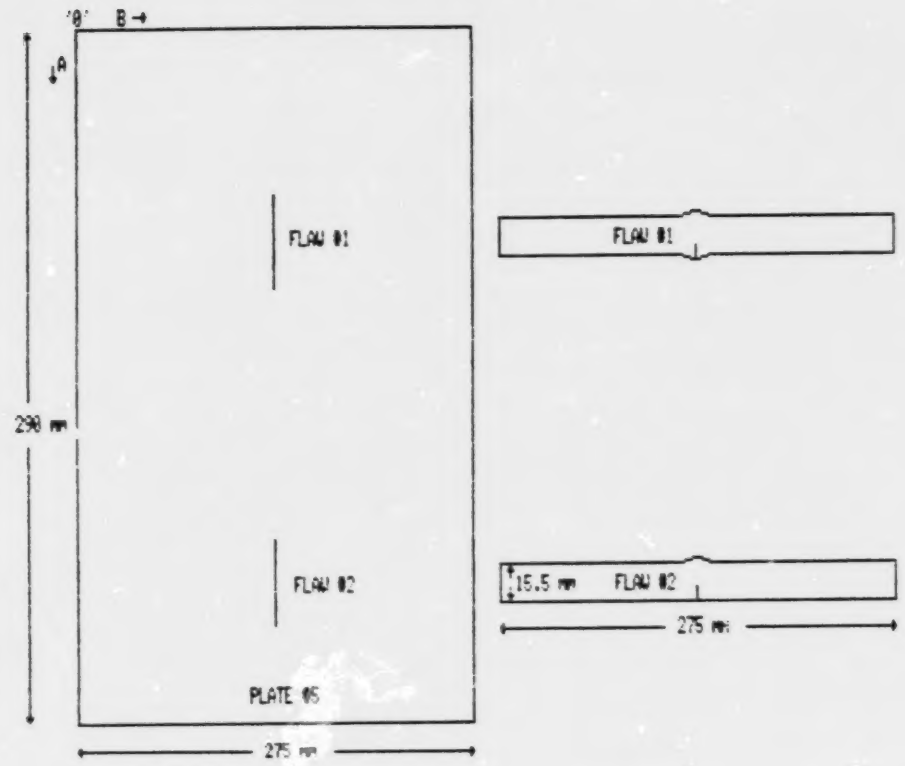


Figure 2: Illustration of Test Plate #5

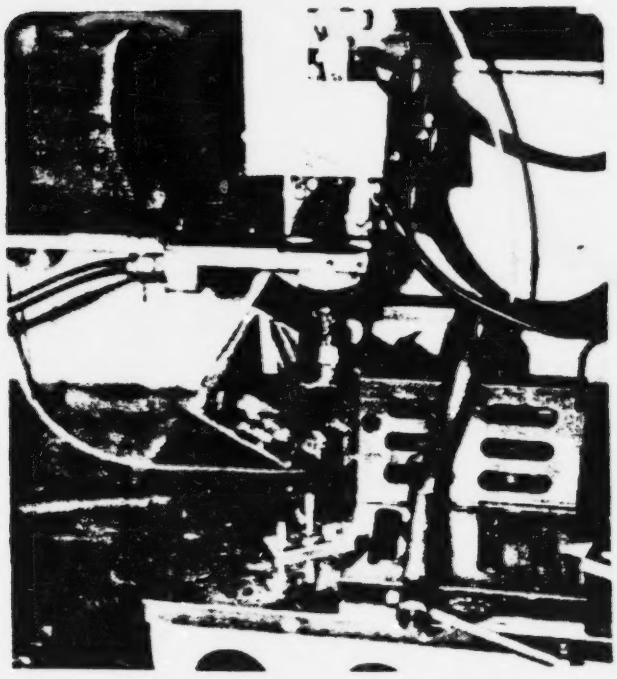


Figure 3A: Photograph of Test Plate #6 During EDM Machining

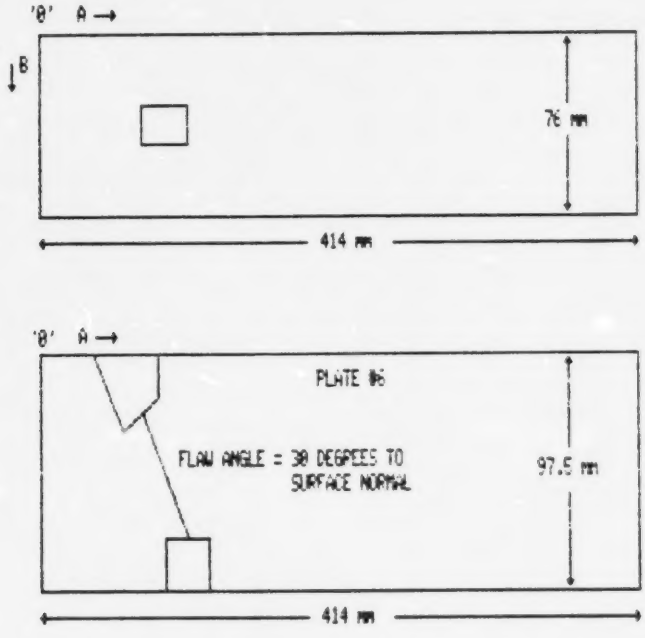


Figure 3B: Illustration of Test Plate #6

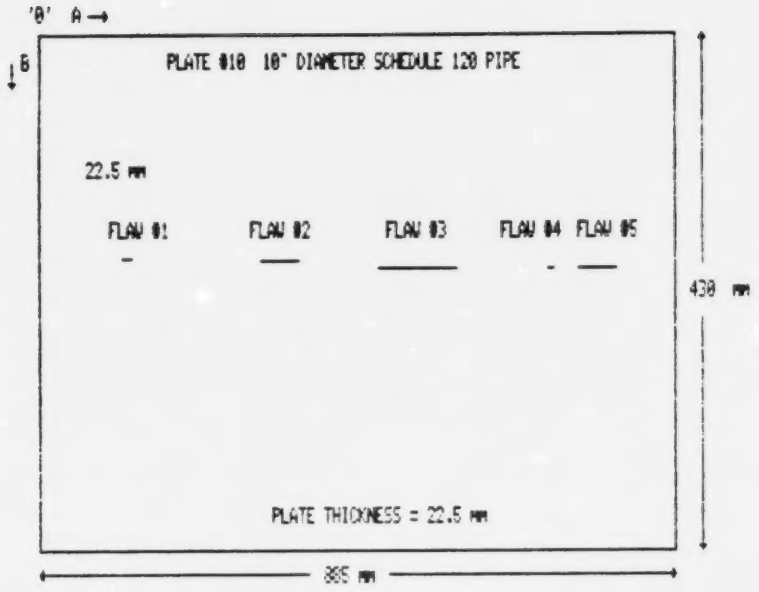


Figure 4: Illustration of Test Plate #10

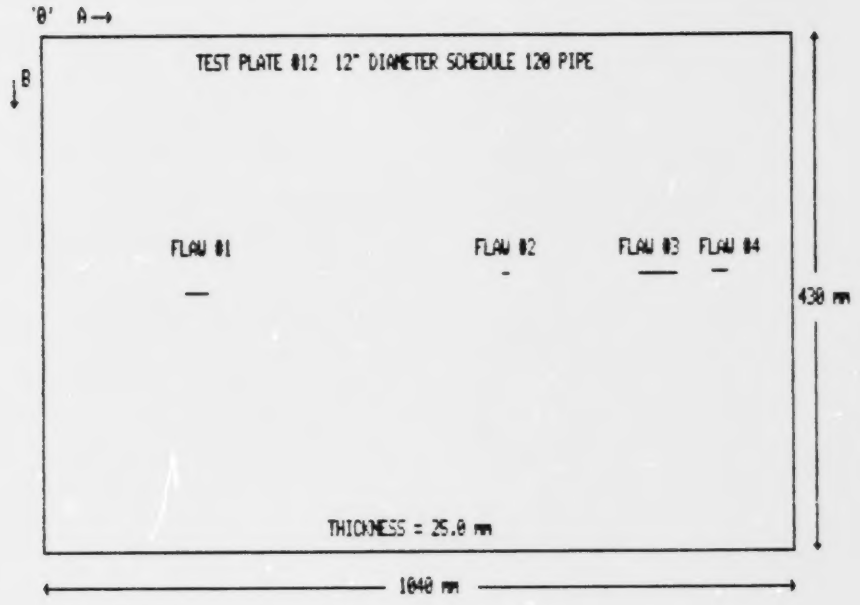
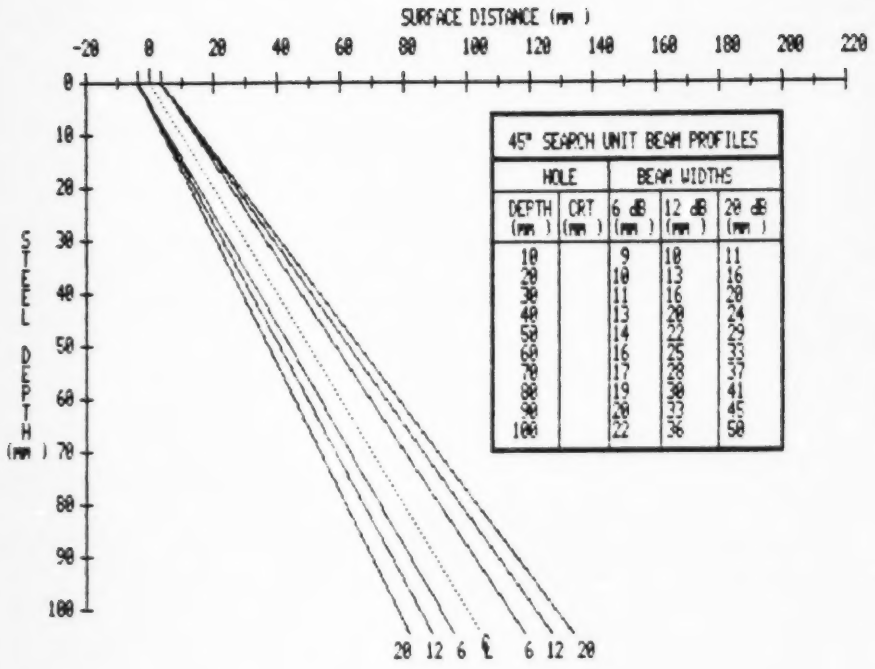


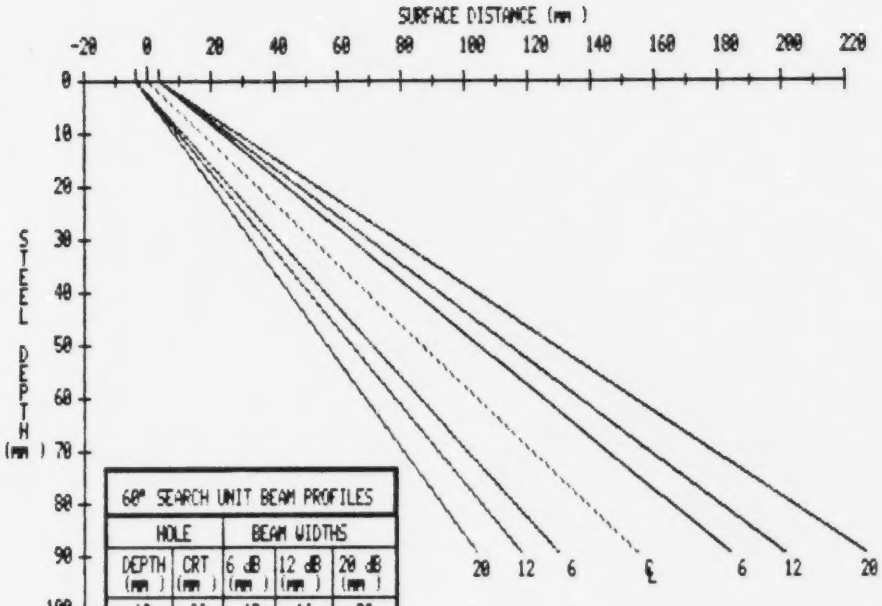
Figure 5: Illustration of Test Plate #12



45° SEARCH UNIT BEAM PROFILES

HOLE		BEAM WIDTHS		
DEPTH (mm)	CRT (mm)	6 dB (mm)	12 dB (mm)	20 dB (mm)
10		9	10	11
20		10	13	16
30		11	16	20
40		13	20	24
50		14	22	29
60		16	25	33
70		17	28	37
80		19	30	41
90		20	33	45
100		22	36	50

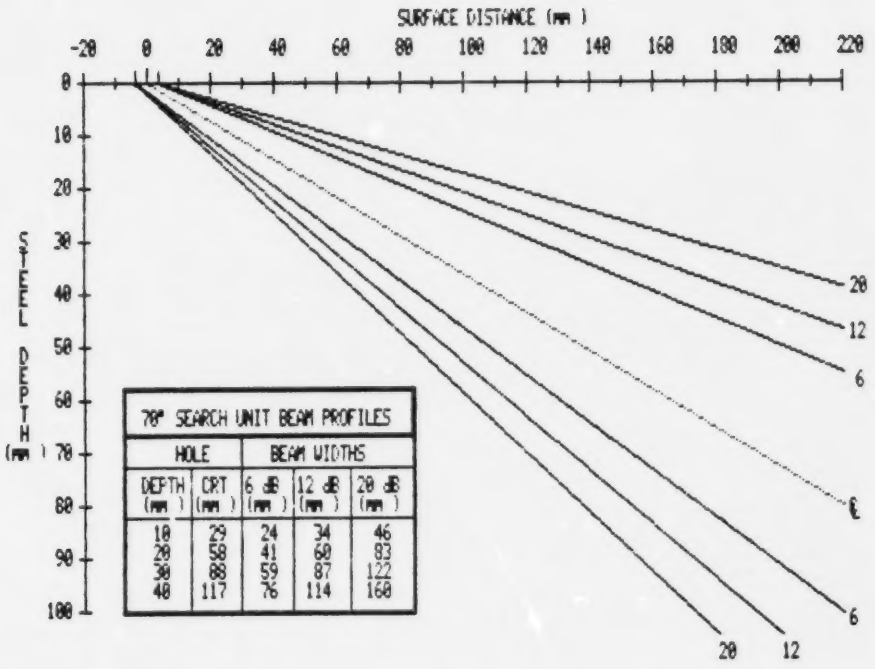
Figure 6: Average Beam Profiles of 45 Degree, 12.7 mm , 2.25 MHz Search Unit



60° SEARCH UNIT BEAM PROFILES

HOLE		BEAM WIDTHS		
DEPTH (mm)	CRT (mm)	6 dB (mm)	12 dB (mm)	20 dB (mm)
10	20	13	16	20
20	40	18	24	33
30	60	23	33	46
40	80	28	41	59
50	100	33	50	72
60	120	39	58	85
70	140	44	67	98
80	160	50	75	111
90	180	55	84	124

Figure 7: Average Beam Profiles of 60 Degree, 12.7 mm , 2.25 MHz Search Unit



70° SEARCH UNIT BEAM PROFILES

HOLE		BEAM WIDTHS		
DEPTH (mm)	CRT (mm)	6 dB (mm)	12 dB (mm)	20 dB (mm)
10	29	24	34	46
20	58	41	60	83
30	88	59	87	122
40	117	76	114	160

Figure 8: Average Beam Profiles of 70 Degree, 12.7 mm , 2.25 MHz Search Unit

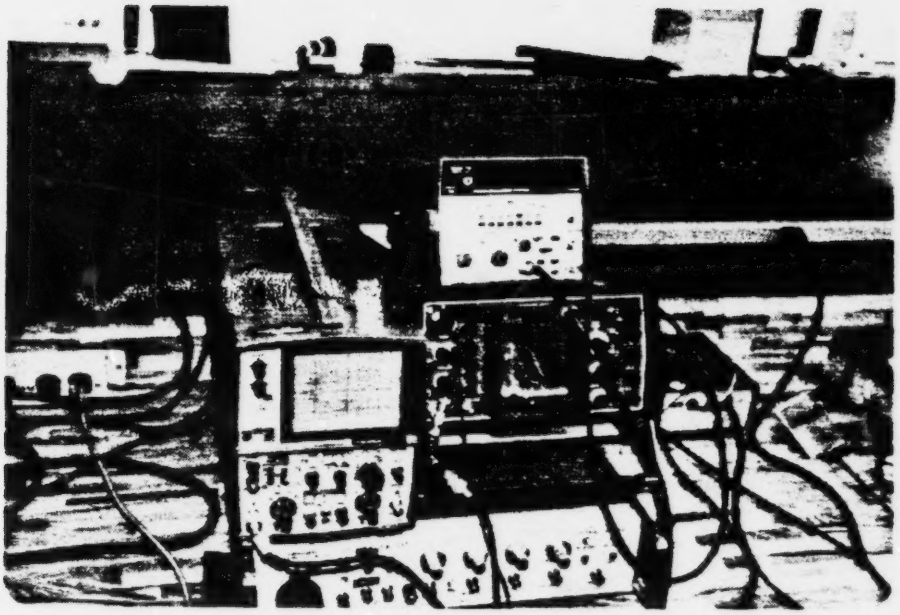


Figure 9: Photograph of Ultrasonic Data Recording System

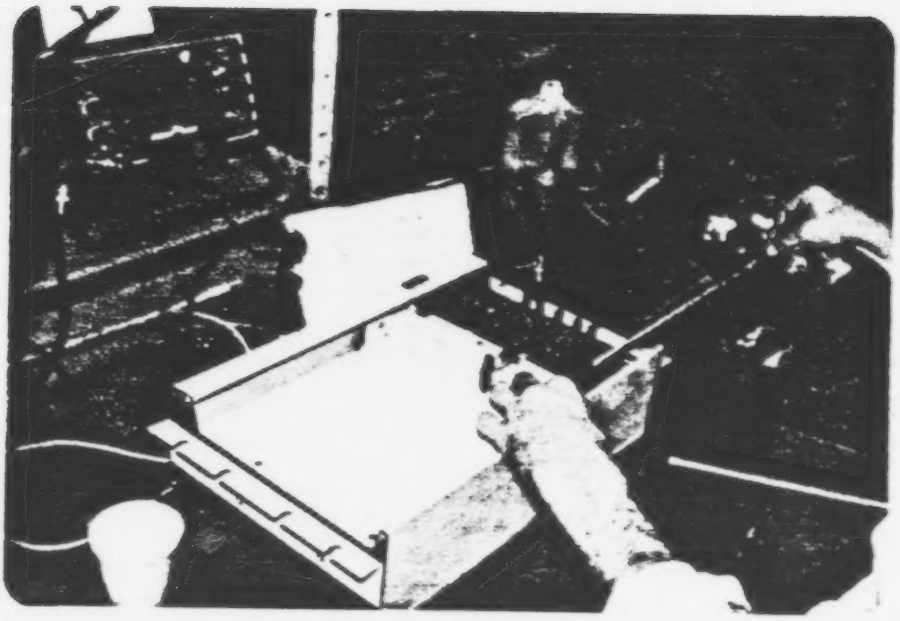


Figure 10: Photograph of Length Measurement in Progress

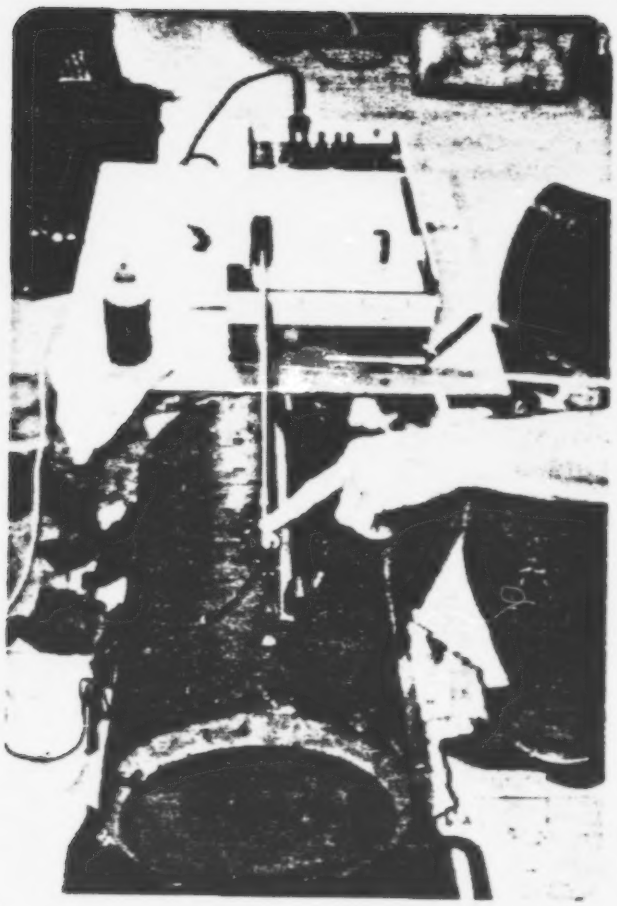
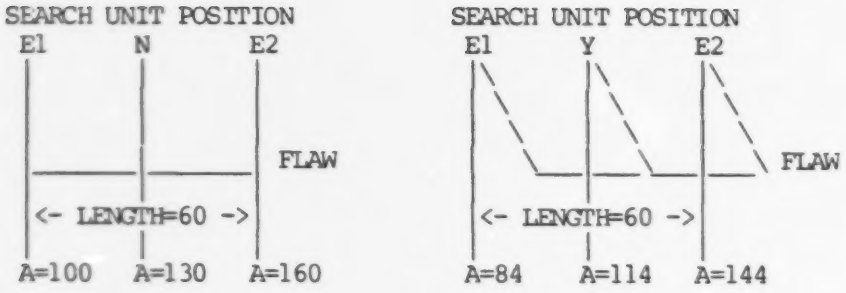


Figure 11: Photograph of Vertical Extent Measurement in Progress

Figure 12: Conversion of Analog Signature Plots into Digital Data



Case 1 - Normal Incidence

Search unit at position N detects flaw at normal sound beam incidence.

Search unit notes flaw ends at search unit positions:
E1 (A coordinate = 100 mm)
E2 (A coordinate = 160 mm)
Flaw length noted as 60 mm and position is correct.

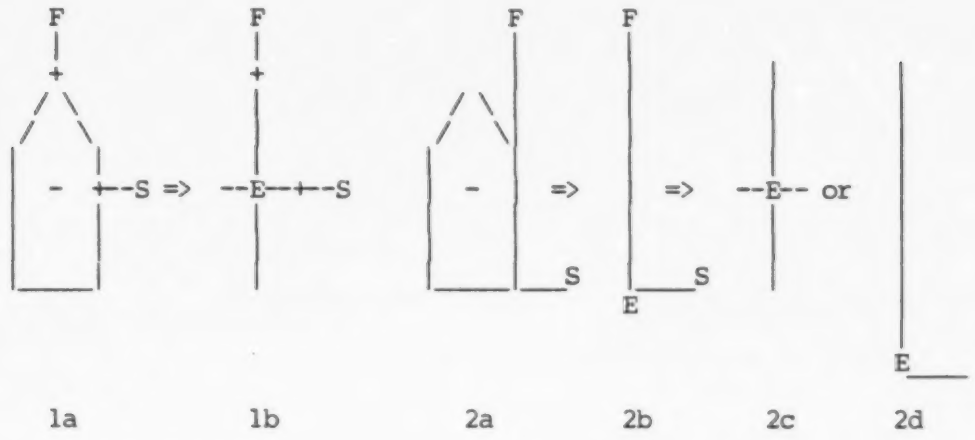
Case 2 - Yaw Angle Incidence

Search unit at position Y detects flaw at some yaw angle from normal incidence.

Search unit notes flaw ends at search unit positions:
E1 (A coordinate = 84 mm)
E2 (A coordinate = 144 mm)
Flaw length noted as 60 mm but position is incorrect.

Figure 13: Flaw Location Error Due to Search Unit Yaw Angle

NOTE: F = Front centre of search unit.
S = Side exit point marked on search unit.
E = Exact point of sound exit from search unit.
=> = symbol for "leads to".



Case 1: Good Action

Case 2: Bad Action

1a: Operator marks the front centre (F) and side exit point (S).

1b: Operator removes search unit and extends lines through marks (F) and (S) to find correct sound exit point (E).

2a: Operator draws lines along the side (F) and end (S) of the search unit.

2b: After removal of search unit from work piece, lines (F) and (S) remain. If operator neglects to correct for displacement of these lines then the sound exit point (E) is incorrect.

2c: After proper correction for search unit half width and the length from end to exit point, the correct sound exit point (E) is determined.

2d: If the operator makes an improper correction (add instead of subtract) then sound exit point (E) is wrong.

Figure 14: Flaw Location Error due to Inspector Improper Marking Practice

DEFINITIONS

The following are definitions of the terms used in this report. These definitions generally follows those of ASME Section XI.

Nondestructive testing - the performance of radiography, ultrasonic, liquid penetrant, magnetic particle, etc.

Examination - the performance of visual observation, measurement and nondestructive testing.

Evaluation - the application of acceptance standards to an indication for the purposes of determining whether an imperfection is acceptable.

Discontinuity - a localized change in the physical properties of a material.

Imperfection - an inhomogeneity in a material or weld.

Indication - the evidence or response obtained by the application of a nondestructive examination that may reveal the presence of a flaw or surface degradation.

Recordable Indication - an ultrasonic indication of sufficient amplitude such as to require recording as per code documents.

Reflector - any sound reflecting object which causes an ultrasonic indication.

Echo - the ultrasonic response (indication) observed on the instrument screen obtained by ultrasonic detection of a reflector.

Flaw - an imperfection, discontinuity, irregularity or fault in the normal physical structure and is detectable by nondestructive examination.

Laminar flaw - planar flaws that are oriented within 10 degrees of a plane parallel to the surface of the component.

Planar flaw - a flat two dimensional flaw oriented in a plane other than parallel to the surface of the component.

Nonplanar flaw - a flaw oriented in more than one plane.

Coplanar flaws - two or more flaws lying in the same plane which are oriented in the through-wall direction (normal to the surface) of a component.

Linear flaw - a flaw having a finite length and narrow uniform width and depth.

Surface flaw - a flaw that either penetrates the surface or is less than a given distance from the surface.

Discontinuous flaw - a flaw which appears intermittent or not continuous, broken in closely spaced parts.

Multiple flaws - two or more proximate discontinuous flaws.

Defect - a flaw of such size, shape, orientation, location or properties as to exceed the acceptance standards and is therefore rejectable.

Tip - an end of a linear flaw.

Transducer - a piezoelectric element housed within a protective case which converts electric pulses into ultrasonic pulses and visa versa.

Wedge - usually an angled plastic wedge which is fitted to a transducer in order to produce an angle sound beam in the material under test.

Search unit - may be a transducer or combination of transducer and wedge used for the ultrasonic inspection of material.

Couplant - refers to the liquid used between the search unit and the material to enhance the efficiency of acoustic energy transfer between them.

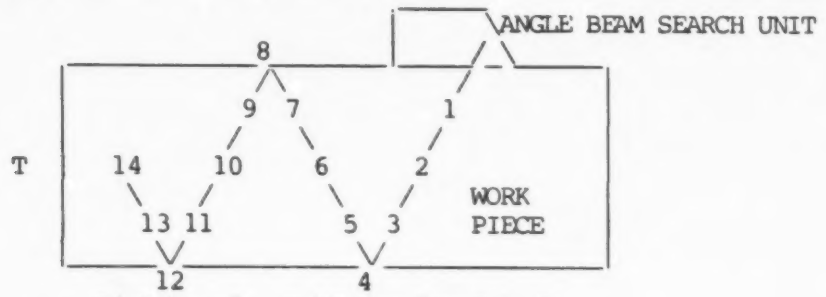
Work piece - the component undergoing nondestructive testing.

Flaw detector - synonymous for an ultrasonic instrument used to detect discontinuities in a material.

CRT - means Cathode Ray Tube, ultrasonic instrument screen, or the screen displayed distance between the search unit and an ultrasonic indication.

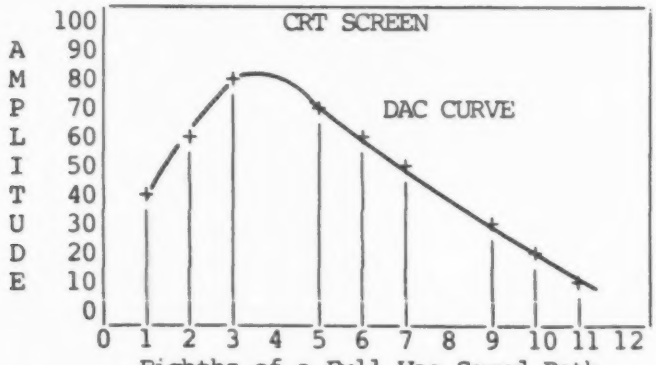
T - synonymous for Thickness of the work piece or calibration block.

Vee Path - refers to distance from an angle beam search unit, measured along the centre line of the sound beam. The sound path is like the letter "V" and a full V path is considered to be divided into eight equal parts (e.i., 8 eigths). Thus, a CRT distance of 0/8ths refers to sound at the search unit, a CRT distance of 4/8th refers to sound one thickness (T) into the the work piece, 8/8th refers to sound at the search unit surface of the work piece after reflection from the opposite side. For example, a reflector may be noted as being at a CRT of 6/8th vee path (i.e., located at 1/2T).



Eighths of a Full Vee Sound Path

DAC - refers to a Distance Amplitude Correction (DAC) curve which is draw on the instrument screen. The DAC curve compensates for the decrease in indication height with CRT distance due to material attenuation and sound beam spread. A calibration block containing identical reflectors at different distances is scanned. A continuous curve (DAC) is drawn through those screen points where it was noted that a maximum amplitude response from reflectors was obtained.



Eighths of a Full Vee Sound Path

Basic Block - refers to a calibration block that is fabricated from a defect free offcut of the material to be inspected or defect free material that possesses attenuation, velocity and surface conditions representative of the material to be inspected. The basic block is used to construct a DAC curve which is then used to assess the severity of indications in the work piece.

Primary Reference Target - refers to the ultrasonic reflector upon which a DAC curve is based. For example, the primary reference target (reflector) may be a 3 mm diameter side drilled hole at 3/4 T in basic block #123, to be shot at 3/8th of a full vee sound path.

Primary Reference Level - refers to percentage of full screen height that the maximized indication from the primary reference target is to be set at. This level is usually 80% of full screen height (FSH).

Primary Reference - refers to the combination of primary reference target and primary reference level. For example, the primary reference may be 80% FSH response from the 3 mm diameter side drilled hole at 1/2T in basic block #123, shot at 6/8th vee path. The primary reference is most important because it establishes the sensitivity and shape of the DAC curve from a basic block. The DAC curve is then used to assess the severity of indications in the work piece.

Coordinates (A, B) - refers to orthogonal system of coordinates designated 'A coordinate' and 'B coordinate' with reference to an ultrasonic datum mark 'O' stamped upon the work piece. An ultrasonic indication is recorded in terms of search unit position upon the work piece with reference to A and B coordinates. For welds being scanned with the search unit pointed normal to the weld, a changing A coordinate reveals that the search unit is moving parallel to the weld, while a changing B coordinate reveals that the search unit is moving towards or away from the weld. To determine the location of the reflector within a work piece requires knowledge of the search unit A and B coordinates, CRT distance and search unit angle.

Size (flaw) - refers to the largest dimensions of a flaw, usually specified by length and vertical extent.

Length (flaw) - refers to the largest dimension of a flaw in the A, B coordinate plane (parallel to the surface). Length is determined by moving the search unit laterally (right and left), from the position of maximum echo amplitude, at right angles to the sound beam until the screen indication has decreased a certain value.

Vertical extent (flaw) - the largest dimension of a flaw in a plane other than the A, B coordinate plane, i.e., at some angle to it. Vertical extent is determined by moving the search unit forward and backward, from the position of maximum echo amplitude, parallel to the direction of the sound beam until the amplitude of the indication has decreased to a certain value, e.g., 6 dB. In this report vertical extent is usually shown as the total surface movement distance of the search unit as the sound beam sweeps across the flaw.

Through wall dimension (flaw) - the largest dimension of a flaw in the vertical plane.

FSH - abbreviation for Full Screen Height. During calibration it is customary to set the maximized indication at 80% of the available 100 unit height of the instrument screen, i.e., 80% FSH.

ISI - abbreviation for inservice inspection.

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